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# Results of a Manned Over Pressurization Event in the Extravehicular Mobility Unit Space Suit Assembly

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**The Neutral Buoyancy Laboratory (NBL) is a 102 x 202 x 40-foot-deep tank holding over 6 million gallons of water used to simulate weightlessness for Astronaut training. The maxim "Train Like You Fly" refers to the desire to have the suit perform, during training, as close as possible to how it performs during an Extra-Vehicular Activity (EVA), particularly with respect to mobility. Therefore, the Space Suit Assembly (SSA) used in the NBL is a downgraded hardware version of the flight SSA; it is not designed for the NBL environment or operations. A classification system defines the flight Space Suit Assembly hardware as Class I, and the NBL training hardware SSA as Class IIIW.**

**On July 20, 2017, during a manned training event in the NBL, the SSA was inadvertently over-pressurized to 22 psid; normal operating pressure being 4.3 psid. The suit subject was removed from the suit with no injury. The event was investigated by a NASA Mishap Team. The Team investigated common causes and differences between the Class I and Class IIIW Extra-vehicular Mobility Unit (EMU). The investigation determined that the event was limited to Class IIIW hardware and its external flow-controlled open loop ventilation systems. The flight EMU is a pressure regulated closed loop ventilation system. This paper will examine the differences between the Class I and Class IIIW SSA hardware and provide details of the Mishap Investigation. Corrective actions taken to mitigate risk with hardware, operations, and hazard documentation will be discussed.**

## Nomenclature

*acfm* = Actual Cubic Feet per Minute
*ECS* = Environmental Control System
*EMU* = Extra-vehicular Mobility Unit
*EVA* = Extra-Vehicular Activity
*HUT* = Hard Upper Torso
*ISS* = International Space Station
*LCVG* = Liquid Cooling Ventilation Garment
*NBL* = Neutral Buoyancy Laboratory
*MPT* = Manned Pressurized Time

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*MWC* = Multiple Water Connector
*psi* = Pounds per Square Inch
*psid* = Pounds per Square Inch Delta
*scfm* = Standard Cubic Feet per Minute
*SSA* = Space Suit Assembly
*TMG* = Thermal Micrometeoroid Garment
*TRR* = Test Readiness Review
*WLVTA* = Water Line Vent Tube Assembly

## I. Introduction

**Figure 1. Weightless Training for Apollo 17, 1972.**

THE mission of the Neutral Buoyancy Laboratory (NBL) is to prepare for space missions involving Extra Vehicular Activities (EVA)s through simulation of weightlessness. Weightless training has been a part of mission preparedness since the Gemini program. The Neutral Buoyancy Simulator at Marshall Space Flight Center was used from 1968 to 1997. The Water Immersion Facility (WIF) was used at JSC for Gemini and Apollo training. From 1980 through 1998 training for Space Shuttle and International Space Station (ISS) missions took place at the Weightless Environment Training Facility (WETF) at NASAs Johnson Space Center. In 1997, the Sonny Carter Training Facility was opened. It houses the 6.2 million-gallon NBL diving tank that is 202 feet long, 102 feet wide, and 40 feet deep. The NBL is large enough to contain a full-scale mock-up of the ISS and other vehicles that are placed in the tank for the purposes of training. The environment is chemically treated to prevent contamination of equipment and is maintained at 82 to 88 degrees Fahrenheit.[1] Crew are suited in flight-like Space Suit Assemblies (SSAs), the mobility portion of the Extravehicular Mobility Unit (EMU). The combination of the gas filled volume of the SSA, with added weights and foam, creates multi-axis neutral buoyancy underwater corrected for righting moments. The suited crewmember neither sinks nor rises with no one part of the suit rotating toward the surface.

Whereas EVA training for Shuttle flights involved about twenty NBL runs to practice tasks associated with particular EVA missions, ISS training includes a broader range of skills proficiency to respond to a number of potential repair scenarios, as well as development of timelines and training for specific EVA missions. Assigned ISS crew perform nine NBL training runs before launch.[2] Training is physically demanding and hazardous, with NBL training runs lasting up to 6 1/2 hours. The most serious hazards involving the SSA include the possibility of loss of breathing gas due to equipment failure and the possibility of rapid decompression or injury due to suit rupture. Hazards are controlled by SSA lab testing prior to events and a robust set of procedures carried out by a highly trained team of NBL personnel from various disciplines. Each training event begins with a crew physical, familiarization overview, and a pre-dive briefing. An end-to-end checkout with the suit and facility is performed followed by suit donning. Water immersion and neutral buoyancy weigh-outs are then completed as the EVA training begins. Safety procedures provide for emergency extraction from the water and from the suit should a critical problem arise with the SSA or facility supply.

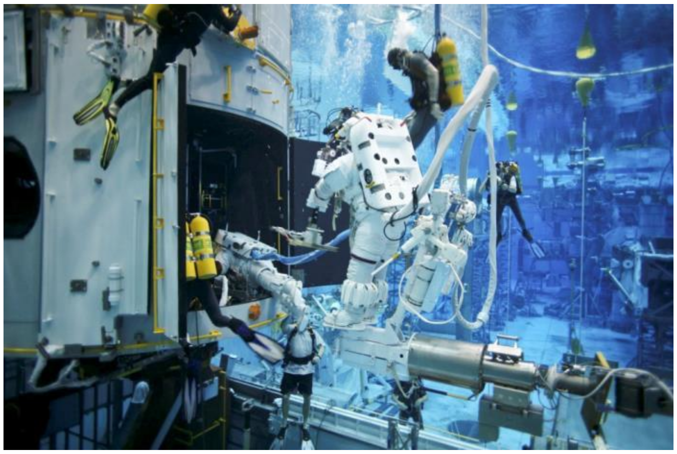

**Figure 2. Crew Training in the NBL.**

## II. NBL Hardware

EMU hardware is classified as I, II, III or IIIW depending on the controls for its intended use and criticality. Hardware used for flight EVA must be Class I, while vacuum chamber hardware can be Class I or II. Class IIIW EMU hardware is controlled, but to a lesser extent than Class I or Class II. Class IIIW categorization allows hardware that cannot meet all Class I or Class II requirements to be used in certain hazardous testing, such as the NBL. Class III hardware is uncontrolled.

In the NBL, the functions of gas supply and return, water supply, communication, and telemetry are provided by facility umbilical and Environmental Control Systems (ECS). Therefore, the Display and Control Module (DCM) is volumetric representation rather than functional Class IIIW hardware. The EMU NBL Primary Life Support Systems (PLSS) is also volumetricly equivalent to a flight PLSS, but contains internal hoses to connect the inlet and outlet umbilical gas and water flow to the suit. The NBL PLSS also provides a non-flight-like pressure relief valve for suit over pressure protection. . In contrast, the SSA is generally Class I flight hardware that has been downgraded at the expiration of flight certification for continued use as Class IIIW hardware.

### A. Life Support

The NBL SSA is pressurized with Nitrox (oxygen enriched air) to a pressure of 4 psi above the ambient pressure at depth. Gas flow is regulated to 6 acfm. The pressurized state of the NBL SSA is therefore very similar to the flight SSA that is pressurized with pure oxygen to 4.3 psi with a flow rate of 6 acfm. However, the similarities end there. The primary difference being that the NBL system is flow regulated whereas the flight system is pressure regulated. Additionally, the flow rate (scfm) and pressure must be varied throughout the NBL run to compensate for water depth changes to maintain a constant 6 acfm. The facility system contains a relief valve that is set at 60 psig to protect the system upstream of the suit. Figure 3 shows the vent flow path elements contained in the umbilical, volumetric NBL PLSS, and SSA during NBL operations. The elements common between the NBL system and flight system are the ventilation portions of the SSA.

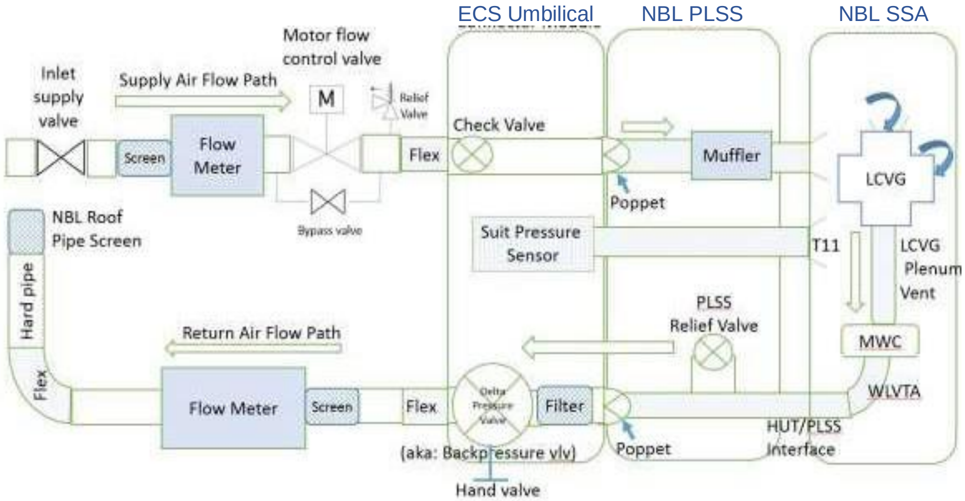

**Figure 3. NBL EMU Ventilation System and Flow Path.**

### B. Class IIIW SSA

SSA hardware is designed to meet EVA environments and requirements and is certified for this use. With few exceptions, SSA hardware is fabricated as Class I. Class I hardware is strictly controlled to allow only documented certified configurations, and to limit life based on both chronologic and operational age (manned pressurized time and cycles). In addition, periodic maintenance, test, and inspection for specific events including pre- and post- flight are imposed. Hardware failing to meet any of these requirements may be downgraded to Class IIIW and used for NBL training.

The most common reason for downgrading hardware to Class IIIW is that it has reached the end of its chronologic life but is still functional. Although SSA hardgoods such as brackets and bearings typically have a 40-year life, softgoods such as fabrics, adhesives, and films are typically certified for only 8 to 10 years of life. It is unusual for SSA hardware to reach the limit of operational life, specifically Manned Pressurized Time (MPT), during ISS EVAs before reaching the chronologic age limit.

Another reason for downgrading hardware is the finding of damage during test and inspection. Damage may be minor but unacceptable for flight such as fraying or abrasion of a pressure barrier layer that can be repaired. The Thermal Micrometeoroid Garment (TMG) layer of the Phase VI Glove does not have an operational life and is often damaged during EVA. A Glove TMG with worn or lifting palm pads may be downgraded for Class IIIW use.

On occasion, new hardware configurations are released. This may be due to design enhancement, replacement of obsolete materials with new materials, or correction of features identified as the cause of a failure. When new hardware is released, prototypes may be made available as Class IIIW for training. Also, depending on the effectivity of the change, previous configurations may no longer be acceptable for flight and may be downgraded to Class IIIW.

In some cases, Class IIIW hardware has been specifically designed for use in the NBL because the water environment is not compatible with the Class I flight design. Examples include the use of plastic zippers instead of brass, Teflon fabric instead of neoprene coated nylon ripstop on the inside layer of TMGs, and fabric buffers on load carrying webbings at bracket interfaces where the lubricity of the water causes premature wear. Other examples include measures to prevent wash-out of lubricants from bearings such as use of a less soluble lubricant and configuration of bearing seals so that the ball bearing race is inside the pressure boundary and protected from the water. Inspection for metal corrosion and provisions for removal of corrosion residue are also unique to Class IIIW hardware.

With these few exceptions, Class IIIW hardware is not designed for the NBL environment. Neither is it certified for the NBL environment. Controls are put in place to ensure that hardware certified for use in the vacuum of space is also safe for use in the NBL. Requirements for test/inspection of class IIIW hardware and annual Test Readiness Reviews (TRRs) ensure system safety.

### C. NBL Hardware Controls

Class IIIW NBL hardware is controlled. Reasonably, the controls are relaxed from the controls imposed on Class I flight hardware. A summary of the differences between Class I and Class IIIW SSA hardware is shown in Table 1. There are limited controls on the configuration of downgraded Class I hardware and usage is not documented as it is for flight hardware. There are no chronologic life limits however usage life is controlled by inspection and maintenance every 40 hours (annually for helmets). Prior to an NBL training event, Class III gear is tested and inspected similar to, but to a lesser extent than pre-flight. Minimum criteria are reduced and allow higher leakage rates and non-structural damage to components. Processing and operations with the NBL SSA are controlled by the EMU

**Table 1. Comparison Between Class I and Class IIIW Hardware Usage.**

| Control | Class I | Class IIIW |
|---|---|---|
| Configuration Control | Current certified configuration only, documented, and reviewed pre-flight | Limited to safety critical changes |
| Leakage Testing | Testing of each SSA subcomponent (i.e. arm, leg) at completion of assembly or re-assembly. Pre-flight testing following structural test at the level of assembly shipped to ISS. | Following structural test, the allowable pre-test leakage rates are 2 times flight allowables for SSA components and 1.5 times for bearings and disconnects. |
| Pre-Flight Inspection<br>(Pre-Event Inspection for NBL) | External visual inspection of structural restraint system, disconnects and bearings must meet minimum requirements for damage and wear. Interfaces are verified. Bearings and assembly screws are checked for proper torque. Structural test while pressurized to 1.5 times normal operating pressure. | External visual inspection of structural restraint system and disconnects. Damage to non-structural components and external appearance (cleanliness, wear) are not a concern. Re-verification of screw torque not required. Structural test while pressurized to 1.5 times normal operating pressure |
| Periodic Maintenance and Inspection | Comprehensive visual inspection of each SSA component disassembled to the extent that all critical surfaces, brackets, fasteners, and bearing seals are exposed. Maximum of every 229 hours (equivalent to 25 EVAs) but often more frequently due to material limits or known wear. | Complete disassembly and inspection every 40 hrs. of operation. Inspection of structural restraint system for obvious signs of damage. Maintenance performed in accordance with Class I procedures with the exception that thread lock is not used, and screw torque is not recorded. |
| Life Limits | Adequate chronologic, operational, and MPT must remain prior to flight so that no maintenance or inspection is required during hardware stay on ISS | No chronologic life limits. Operational life is extended in 40-hour increments based on passing inspection. Helmet is inspected yearly. |

Processing Requirements and Constraints document, and NBL Operating Plan. Any condition that has the possibility of harming personnel or equipment due to NBL suit operations is detailed in the Hazard Analysis for Class IIIW NBL Space Suit Assembly, as well as several facility hazard analyses and Failure Modes and Affects Analyses.

## III. Over pressurization Event

On July 20, 2017, two crewmembers began a training NBL run at 8:47 am. Water ingress was shortly after 9:00 am with the suit pressurized to a nominal 4 psid. Approximately thirteen minutes later, at a depth of approximately 35 feet, weigh-out was performed with crewmember EV2 on his back. Pressure began increasing in the suit leading to an audible alarm. As the pressure increased above 5.2 psid, where the relief valve should have opened, no venting occurred. The suit became stiffer and more buoyant. Pressure in the suit reached 22 psid. At this point, leakage of the suit became evident with a stream of bubbles emanating from the shoulder area. Environmental Control System (ECS) operators reduced gas flow to the suit, reducing suit pressure, and Safety Divers brought EV2 to the surface. The crewmember doffed the suit without injury and was cleared by the Medical Team.

Immediately, the hardware was quarantined, the facility was secured, and use of both Class I and Class III hardware and facilities were placed on hold. A Mishap Investigation Team (MIT) was formed to investigate root cause. The MIT quickly created and assessed a fault tree, finding no potential faults that would result in over pressurization of the Flight EMU. The NBL is a flow-controlled, open loop system whereas the Flight EMU is a pressure-controlled, closed loop system with no common controlling components. Operations on ISS and in the two NASA vacuum chambers were resumed while the team continued to investigate the fault tree for NBL operations. The MIT concluded their investigation in November of 2017. The failed hardware was found to be a portion of the SSA ventilation system termed the Water Line Vent Tube Assembly (WLVTA) which had become blocked. The flow restriction upstream of the PLSS relief valve caused the pressure increase and prevented the relief valve from functioning (see Figure 3). The MIT identified two root causes, three proximate causes, one intermediate cause, and two contributing factors to the NBL over-pressurization mishap. The root causes were insufficient identification and control for all points of flow restriction within the system that could result in an increase in suit pressure, and insufficient criteria for continued use of limited life hardware in the Class IIIW EMU.

### A. Failed SSA Hardware

Although the method of pressurizing the Class IIIW NBL SSA is different than the pressure system of the EMU, the static portion of the flow system in the SSA is the same for Class I and Class IIIW SSAs. Flow, at 6 acfm, enters the SSA behind the neck through a vent duct embedded in the fiberglass Hard Upper Torso (HUT). Return flow is picked up at screened vent duct openings on the arms and boots of the Liquid Cooling and Ventilation Garment (LCVG), worn by the crewmember inside the SSA. A plenum on the LCVG directs flow from flexible ducts on the arms and legs into a larger vent duct that wraps around the torso. The torso vent duct and water lines of the LCVG connect via a Multiple Water Connector (MWC) quick disconnect to the WLVTA portion of the system in the HUT. The WLVTA is shown between the HUT and the MWC in Figure 4. Vent flow in the WLVTA then travels through static passages in the HUT, PLSS and return umbilical. The PLSS relief valve is located near the PLSS-umbilical interface on gas return.

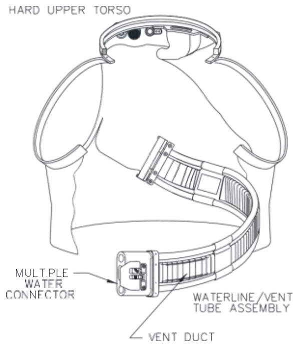

**Figure 4. WLVTA portion of SSA Ventilation System**

Although the static vent duct design in the Class IIIW SSA is like the Class I SSA, the differences in the pressure systems result in a vent duct blockage having opposite effects. While the WLVTA blockage caused over pressurization in the NBL, the same blockage would cause low vent flow in the Flight EMU, without affecting suit pressure.

The WLVTA installed in EV2’s HUT was found to be an early configuration manufactured in 1978 or 1979. The configuration was fabricated with an internal bladder layer that remained part of the assembly. It is this bladder layer that became delaminated and caused blockage of the vent duct. As early as 1980, a previous failure with similar hardware resulted in a change to the manufacturing process to eliminate the internal bladder layer and to perform in-process testing to check that every WLVTA does not delaminate. In the following years, additional changes were made so that current Class I WLVTAs are neither the same material nor the same configuration as the failed Class IIIW WLVTA.

## B. Disposition of Over Pressurized SSA Components

A team of EMU engineers evaluated the hardware that was subjected to the 22 psid suit pressure. Documented structural data indicates that there is sufficient margin over the pressure load in all the components except HUT and LTA-side Body Seal Closure. As a result, the HUT and LTA-side Body Seal Closure were permanently removed from service. The suit softgoods items (the waist, brief, legs, boots, gloves upper and lower arms) were removed from the hardgoods and thoroughly inspected. These items exhibited no structural damage except for the gloves which had wear on seams typical of Class IIIW gloves and not believed to be related to the incident. The helmet and hardware items were disassembled and inspected. No structural damage was identified, as was expected given the structural capacity of the equipment. The inspected hardware and softgoods underwent periodic maintenance and testing and were returned to NBL service. There are no plans to return the HUT and LTA-side Body Seal Closure to service.

## C. Cause and Corrective Actions

The corrective actions needed to return to NBL operations and prevent recurrence of the root cause included: removal of all WLVTAs and vent ducts with internal bladders, inspections for collapsed vent ducts, addition of a relief valve directly tied to the HUT cavity, update of hazard analyses to include the risk and control of over pressurization; assessment of the pressure regulation systems at all Class IIIW laboratory sites and modifications of systems as needed to verify that hazard controls are adequate; and a review of life limitations for Class IIIW NBL hardware. Figure 5 shows the proposed NBL vent flow system with the new relief valve. As of October 2017, merely three months after the over pressurization event, all sites have been cleared to return to operations and the Hazard Analysis for Class IIIW NBL Space Suit Assembly JSC 62050 has been revised to include controls for an over pressurization event. Vent system hardware with internal bladders have been removed from Class IIIW service. NASA has elected to resume

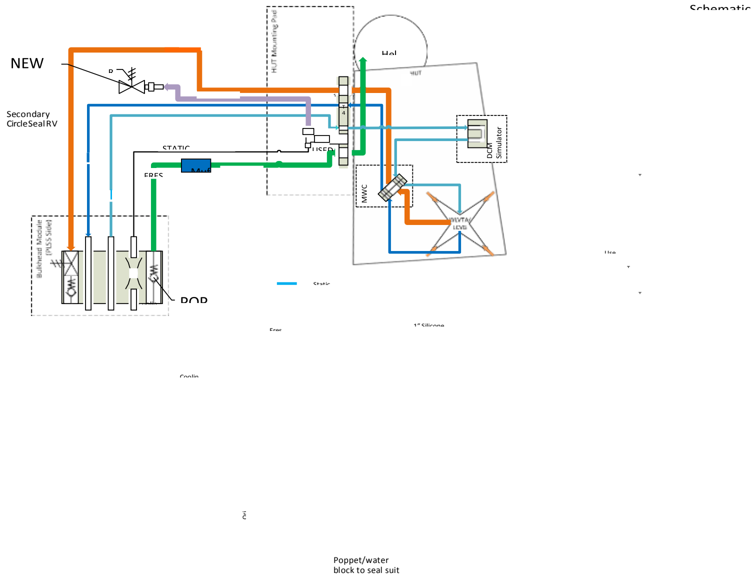

**Figure 5. NBL PLSS Schematic with Additional Relief Valve**

operations at increased risk until a new relief valve system is verified and implemented. A review of NBL hardware limitations is underway.

To place limitations on NBL hardware, it was first necessary to recognize that processing and operations as defined in the EMU Processing Requirements and Constraints Specification, FEMU-R-001, and certification of Class I hardware designs were valid and acceptable for Class IIIW hardware and would not be modified. Using the revised Hazard Analysis, critical components and materials for which failure of redundancies would cause potential crew injury or event termination were defined. Critical hardware must be of an acceptable configuration, age, and condition as shown in Figure 6.

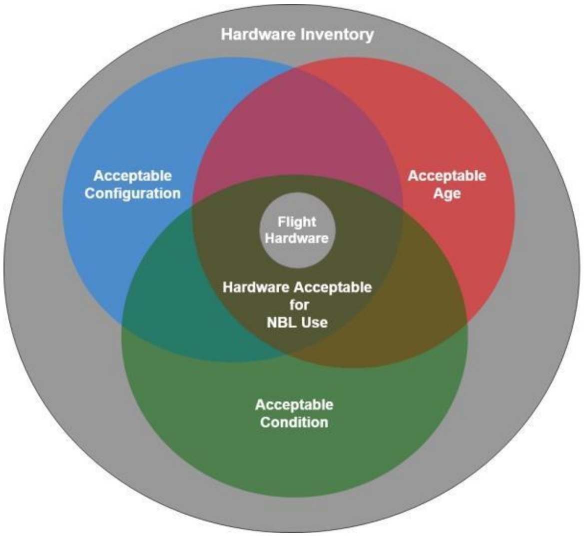

**Figure 6. Acceptability of Class III NBL Hardware.**

Critical configuration changes include those that result from corrective actions for design failures or that eliminate failure modes, and those that improve margin over design requirements. Multiple configurations arising from changes that do not affect failure modes and design requirements remain viable for Class IIIW use. Configurations that predate critical changes should be removed from NBL use.

Age limitations are based on material degradation modes. Degradation modes are correlated with failure modes for components made of critical materials. Some age or usage related failure conditions are screened by existing tests and inspection. For example, the bladder layer of the pressure barrier is made from a nylon material which is susceptible to degradation from chlorinated water. Tearing of the material results in leakage that should be detected during pre-event testing. However, it is possible that the tear initiates during donning and propagates to a substantial leakage during an event. This is an example of material degradation leading to a critical failure mode that cannot be detected, and for which age and operational limits should be established. A full inspection of aged NBL hardware will help establish the age limits for all critical materials.

To establish limits for acceptable conditions, the functions that define critical components must be delineated. Existing procedures that test or inspect each NBL component, and the corresponding pass/fail criteria, must be compared to critical functionalities to assess adequacy of screening procedures. In addition, the inspection/test interval must be assessed. Structural webbings that provide integrity for the restraint layer of the pressure barrier are only fully inspected every 40 hours to the extent necessary to identify visible damage. Pre-event visual inspection of webbings at restraint brackets and structural tests will identify a failed webbing. However, the extent of wear necessary to cause failure of webbings that have been exposed to the NBL water environment during dynamic manned loading is unknown. Class IIIW NBL hardware with critical functions that cannot be adequately screened for unacceptable conditions should be removed from the NBL or, if possible, screening procedures should be updated.

As shown in Figure 5, limits must be based on all three sets of circumstances. A particular wear condition on a component may be acceptable at any age, but the component configuration may not mitigate known failures. An older configuration of hardware may be acceptable if it does not exhibit a certain discrepant condition. In the case of the failed WLVTA that resulted in over pressurization, the proposed hardware limitations would have identified a non-viable configuration, a critical bladder material beyond expected life, and a bladder delamination condition with inadequate screening. By this measure, new Class IIIW NBL hardware limitations seem to be an effective corrective action for the NBL over pressurization event. However, in addition to the research needed to establish recommendations for the limits, the cost and logistical impact to the ISS program must be weighed before the limitations can be implemented. The study to create new age, configuration and condition limitations is still in work.

## IV. Discussion

The effectiveness of neutral buoyancy training is such that all missions involving the potential for EVA are likely to include training at a facility like the NBL at the Sonny Carter Training Facility where crew currently train for ISS missions. Weightless training has changed through the years as missions have evolved. During Apollo missions, each crewmember had just one custom-made training SSA and neutral buoyancy training was just being adopted. Shuttle crewmembers had fewer configurations of SSA components and newer hardware. It has only been with the continued success of the ISS program that it has been possible, if unimaginable, that 30-year old SSA softgoods could be used for hazardous manned training.

NBL operations are less hazardous than EVA and therefore there are less restrictions on the SSA hardware used in the NBL. Never-the-less, NBL training is hazardous and is compounded with hazards specific to the underwater environment. Hazards are controlled by means of the hazard analyses, FMEA/CILs and procedures. A highly trained team of NBL personnel lead by a Test Director and including ECS officers, suit engineers, suit technicians, safety divers, medical and safety operations personnel guarantee that operations are safe. A TRR process also ensures system safety. With a long-lived ISS mission comes the advantage of experience, training, and dedication of support teams who demonstrated no complacency during this over pressurization event and resolved unforeseen risks quickly and safely.

With few exceptions, Class IIIW SSA hardware is downgraded flight hardware. The cost of certifying Class IIIW hardware for its intended use is not justified. The training programs for Shuttle and ISS missions have shown that reliance on Class I design certification is valid with provisions. Provisions include creation of select designs that are less susceptible to NBL environmental degradations and placing limitations on Class IIIW hardware use. Over the history of NBL SSA use, unique designs and limitations have been implemented based on safety and effectiveness or cost drivers. Because of the recent over pressurization event, a concerted effort has been undertaken to inspect NBL hardware and develop comprehensive limitations based on the precept that critical hardware must be of an acceptable configuration, age, and condition. This effort sets a standard for future space suit training programs. Yet, the cost associated with new limitations must be understood.

The expense of Class IIIW hardware must take into consideration the cost of maintenance, test, and inspection; the logistics of downgrading Class I hardware; availability of proper sizing and configurations to prevent injury during training, and the possibility of fabricating new hardware for Class IIIW use. Additional hardware limitations will undoubtedly increase expenses. So too do failures and Mishap Events. The cost of interruption in services, loss of over pressurized hardware, and investigation is significant. Although it is not recommended to change protocol by reducing the number of crew training runs, the training schedule also affects cost. New flight programs will need to make important cost decisions based on training needs and the hardware used in training.

## V. Conclusion

Since Apollo, weightless training has been an effective means for EVA preparation. On the Shuttle and ISS programs, a classification of SSA hardware has been developed for NBL use. As the SSA nears 30 years of service, the NBL fleet of downgraded flight hardware has become less and less flight-like. Adequate controls maintain safety of the Class IIIW NBL fleet, but a recent over pressurization event shows the need for additional limits on the age, configuration, and condition of NBL hardware to improve safety and prevent expense due to loss of hardware and failure investigation. New limitations have cost and logistics impacts that create lessons learned for future flight programs involving EVA. New programs should consider training needs in life cycle analyses regarding the amount and pedigree of training hardware needed and the limitations on its use.

## Acknowledgments

The authors would like to acknowledge the leadership of the NASA NBL Over Pressurization Mishap Investigation Team and the personnel at the NBL and other contractors who worked to quickly and safely resolve this issue.

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