

## ***Long-Term International Space Station (ISS) Risk Reduction Activities***

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### **ABSTRACT**

As the assembly of the ISS nears completion, it is worthwhile to step back and review some of the actions pursued by the Program in recent years to reduce risk and enhance the safety and health of ISS crewmembers, visitors, and space flight participants. While the initial ISS requirements and design were intended to provide the best practicable levels of safety, it is always possible to further reduce risk – given the determination, commitment, and resources to do so. The following is a summary of some of the steps taken by the ISS Program Manager, by our International Partners, by hardware and software designers, by operational specialists, and by safety personnel to continuously enhance the safety of the ISS, and to reduce risk to all crewmembers.

While years of work went into the development of ISS requirements, there are many things associated with risk reduction in a Program like the ISS that can only be learned through actual operational experience. These risk reduction activities can be divided into roughly three categories:

- Areas that were initially noncompliant which have subsequently been brought into compliance or near compliance (i.e., Micrometeoroid and Orbital Debris [MMOD] protection, acoustics)
- Areas where initial design requirements were eventually considered inadequate and were subsequently augmented (i.e., Toxicity hazard level-4 materials, emergency procedures, emergency equipment, control of drag-throughs)
- Areas where risks were initially underestimated, and have subsequently been addressed through additional mitigation (i.e., Extravehicular Activity [EVA] sharp edges, plasma shock hazards)

Due to the hard work and cooperation of many parties working together across the span of more than a decade, the ISS is now a safer and healthier environment for our crew, in many cases exceeding the risk reduction targets inherent in the intent of the original design. It will provide a safe and stable platform for utilization and discovery for years to come. In the following



configurations and flight attitudes required that these modules take the brunt of the MMOD risk. Many discussions ensued as to how to fairly sub-allocate the MMOD risk across the integrated vehicle, recognizing the use of legacy modules and the significant difficulties in re-design. MMOD risk mitigation typically involves the use of additional layers of shielding, which grow the outer mold-line of the module and thereby can create physical packaging issues during launch vehicle integration under shrouds with very small clearances. Shielding modifications can also affect the optical and thermal properties of the module and thereby force significant analysis to verify continued compliance with other performance requirements. On-orbit shielding modification is possible, and we have done it, but it requires the design and fabrication of EVA-installable shields, critical up-mass sacrifices, and finally the execution of significant EVA tasks. Suffice it to say, risk mitigation in the world of MMOD is rather cumbersome and expensive. Furthermore, MMOD risks are primarily statistical in nature, and it is sometimes difficult to get an intuitive feel for the true level of risk associated with particles of various size and material properties impacting the vehicle in various ways, and causing various levels of damage. Depending upon the specifics of the impact and subsequent hole, the consequences can range from a small penetration that can be located and patched with little impact, to a hole large enough and hidden enough to cause loss of a module through hatch isolation, to a hole large enough to force ISS evacuation, and ultimately to near-immediate loss of the crew and vehicle. The range of consequences is very dramatic and significant analysis is required to understand the likelihood of each threshold being crossed.

At the same time, our understanding of the MMOD environment has continued to evolve. ISS experiments, the return of external hardware with long on-orbit exposure times, and post-mission Orbiter inspections all told us that the threat of MMOD was real and getting worse. Fairly recently events, such as the intentional destruction of a Chinese satellite and the inadvertent collision of two other satellites, were also driving factors for a worsening environment.

So, the ISS Program was left to manage a very significant worsening risk, not only driven by a worsening environment and by the increasing size of the vehicle itself, but also a risk that required the expenditure of significant resources. As a commendable example of continuous risk management, in 2012, our partners will be modifying their Soyuz and Progress visiting vehicles, as well as developing and manifesting new Service Module shielding for on-orbit EVA installation on the Russian segment. Furthermore, the development of a new on-orbit crew “push-button” capability to initiate a preset Debris Avoidance Maneuver (DAM) will eliminate the current 24 hour lead time required for orchestrating a DAM and allow the crew to respond to late-breaking conjunction threats from tracked debris. These very substantial mitigation activities target critical risk areas and will significantly improve the ISS safety risk posture.

## 2. ACOUSTICS

Early in the ISS Program, there was significant concern regarding the long term effects of the ISS acoustic environment on crew health. While Program safety requirements dictated the NC-50 criterion (58 dB averaged over any ten-second period) [1] to provide hearing protection that was thought to be technically feasible to achieve, initially there were multiple Noncompliance reports (NCR's) required for both the US and Russian segments of the vehicle. Concerns included both short-term and long-term hearing degradation, inability to hear both conversations and alarms, and psychological stress caused by exposure to excessive noise. Early crews were encouraged to wear hearing protection, and both earplugs and headphones were provided. Program Management, Safety, and the International Partner community worked continuously to build quieter fans, add mufflers, change fan blade materials, and otherwise reduce noise. The results of these efforts can be seen in the following diagrams [2] and [3]:

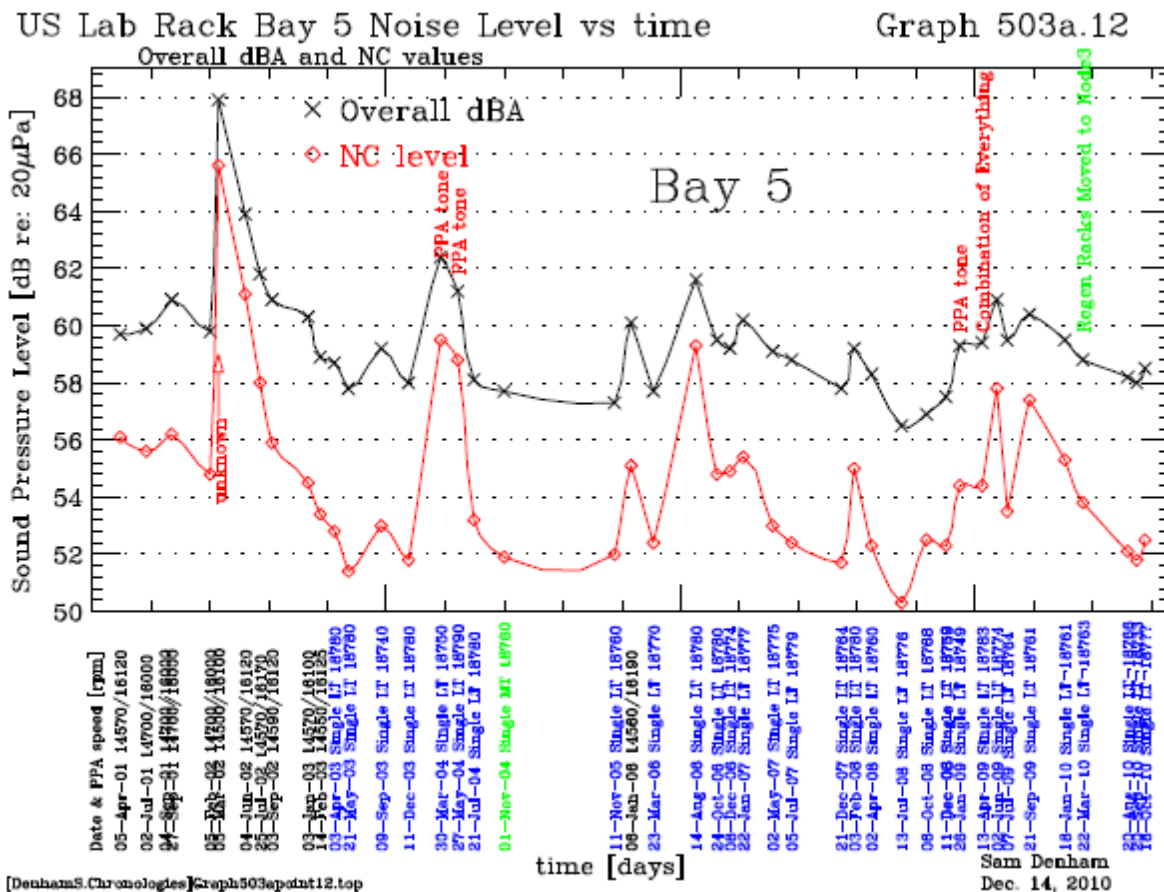
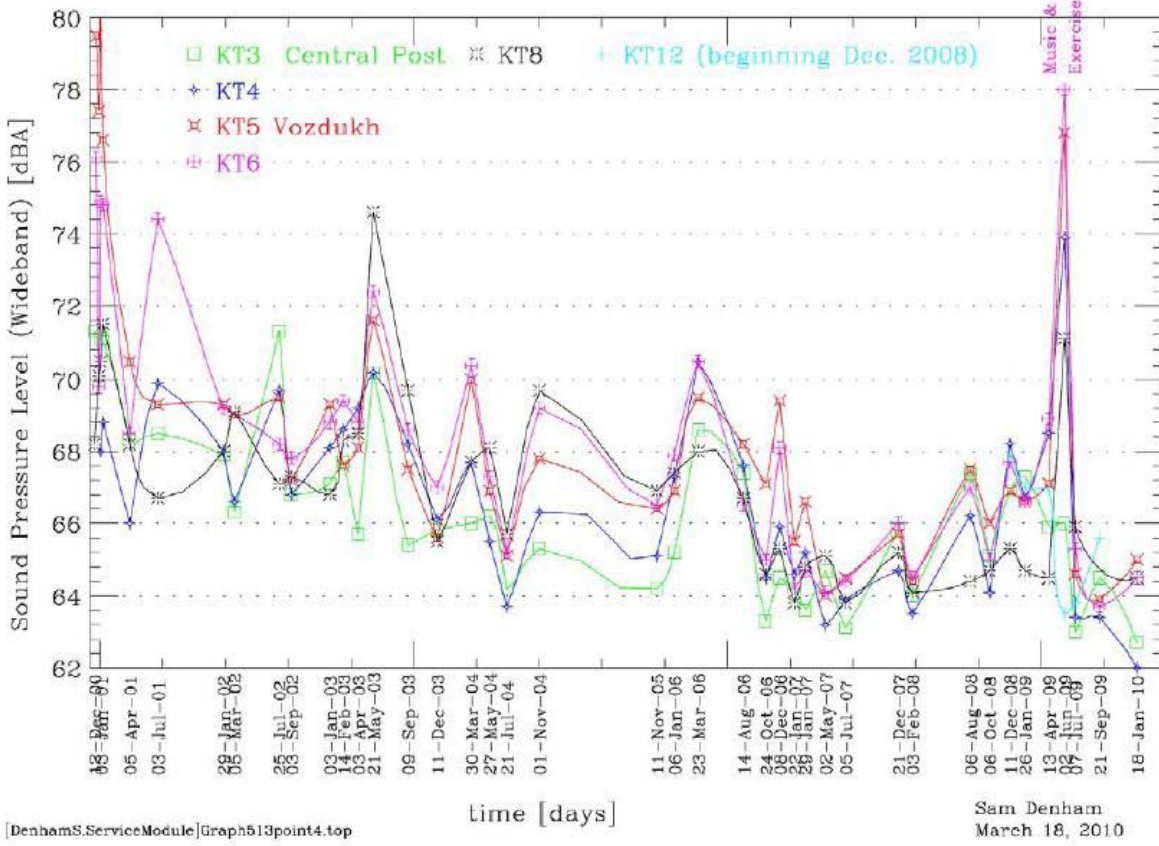
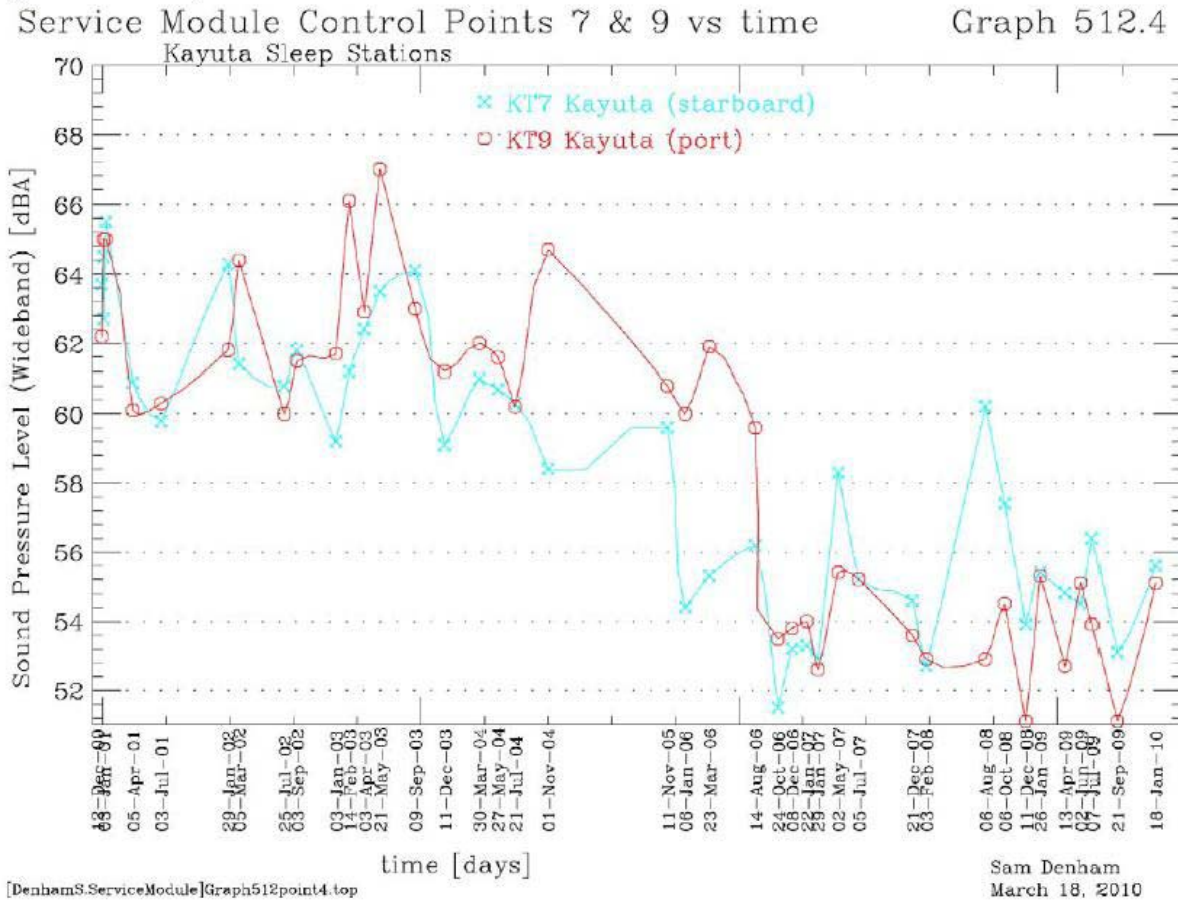


Figure 22. SM Central Control Points vs time  
 Service Module Control Points 3,4,5,6,8,12 vs time Graph 513.4



(Contract Goal = 63 dBA)

Figure 23. SM Kayuta Control Points vs time



(Contract Goal = 50 dBA)

Acoustic sampling is performed over a wide range of locations in both the US, IP, and Russian Segments of the ISS, and these charts represent only a sample. But note the significant reductions achieved over time, particularly in the Russian Segment. USOS and IP elements have achieved full compliance in many areas, and Russian designers are clearly on track to meet their design goals. The graphs above represent over ten years of efforts to bring the ISS acoustic environment into compliance with initial design requirements, and indicate that we are on a path to success. But more importantly, no reports have been made of any crewmember hearing deficits, either short-term or long term. While 100% compliance with the NC-50 criteria has not yet been achieved, significant progress has been made toward preserving crew health.

### 3. TOXICITY HAZARD LEVEL-4 MATERIALS

In the closed environment of the ISS, the release of potentially toxic materials constitutes a significant risk. Since the earliest days of the program, concerns have been expressed regarding the usage and proper containment of especially toxic materials such as ammonia, mercury, and lithium compounds such as those found in high energy density batteries. ISS safety requirements divide potentially toxic substances into five categories:

- a. Toxicity Hazard Level (THL)- 0 – No hazard ( e.g., the release of small quantities of water)
- b. THL-1 – Critical hazard (exposure to minor skin or eye irritants)
- c. THL-2 – Catastrophic hazard (moderate to severe irritation, with the potential for long-term injury)
- d. THL-3 – Catastrophic hazard (systemic toxicity with the potential for long-term injury or illness from the release of solids or non-volatile liquids)
- e. THL-4 – Catastrophic hazard (same as THL-3 but from the release of a volatile liquid, gas, or fumes)

In 2006, in an effort aimed at vehicle-wide risk reduction, the Program Manager directed that all THL- 4 materials be removed from the ISS, as soon as it was possible to do so without impacting ongoing investigations. (Many of these items were batteries containing lithium thionyl chloride and other lithium compounds.) This effort was begun immediately, and completed over the next two years. One may well ask why these items were singled out. After all, the same safety requirements were imposed on THL-4 materials as on all other catastrophic hazards: two fault tolerance or design to minimum risk (either provide triple [and on-orbit verifiable] containment or use a pressure vessel). And the severity of the effect was the same: severe injury or death. The key discriminator in this decision was the combination of lethality and inadequate crew response capability presented by THL-4 materials. A solid or a non-volatile fluid can be safely cleaned up, given the proper crew protection equipment. But a battery that vents lithium thionyl chloride into a habitable volume can cause an immediate and potentially lethal hazard, and can be extremely difficult to clean up, potentially rendering a volume uninhabitable. And while high energy-density batteries are extremely desirable for space applications, the Program Manager determined that this was not a risk trade he was willing to make.

Today, our requirements still do not absolutely forbid the use of THL-4 materials. However, such usage is strongly discouraged, and the Program Manager has reserved the right to review and approve all such proposed applications on a case-by-case basis. Of course, it must be said



that some THL-4 materials still remain onboard, such as the silica gel in the Vozdukh system. Indeed, the biggest such threat is from the ammonia in the US external cooling system. Leakage through internal heat exchangers could introduce significant quantities of ammonia into the cabin creating a potentially catastrophic hazard. But it is not deemed practicable at this time to entertain the idea of changing the basis for external heat rejection in the US segment of the ISS. This risk has been accepted. However, that is not to say that no mitigation has been attempted. As will be discussed in a later section, ammonia masks have been provided and procedures developed for ammonia scrubbing to protect Soyuz egress.

#### **4. EMERGENCY PROCEDURES**

Crew response to on-orbit emergencies such as fire, toxic release, or depressurization, can be complicated and difficult. The changing configuration of the vehicle, the changes in crew size, changes in command, and different spaceflight paradigms involved among our diverse crews all conspire to make the proper and safe response to a wide variety of emergency scenarios a challenging task to implement. We have spent years of discussions with our partners to attempt to revise and improve our ability to respond quickly and correctly in emergency scenarios to ensure crew safety while doing everything possible to preserve an irreplaceable international asset.

Improvements to emergency response procedures have been made continuously since the inception of ISS, but several significant modifications have been made in recent years. Although the risk of an ammonia leak into the habitable volume is very low likelihood, several years ago emergency response procedures and hardware were developed to attempt to adequately protect the crew and vehicle for this scenario. Refinement of the ammonia leak response continues still today, with development of ammonia scrubbing procedures for the Soyuz vehicles actively in work. Ammonia scrubbing capability for the Soyuz vehicles would provide the additional time needed for the crew to perform an orderly undock, rather than an immediate undock with ballistic re-entry. When Russian Segment scrubbing capability is developed in the future, having a Soyuz “clean zone” will allow the crew to stay on-orbit until it is safe to egress the Soyuz vehicle, thus preventing the abandonment of ISS.

Over the past year there has also been an important update to fire response on ISS. In 2009, the Safety & Mission Assurance organization brought forward a risk to the operations community regarding use of hardline oxygen during fire response. Use of hardline oxygen requires the crew to wear a mask that plugs into the ISS oxygen system to provide breathing oxygen to the crewmembers during a fire scenario. Due to the design of the mask, significant oxygen leakage from the mask is expected in this scenario and will rapidly increase the oxygen concentrations throughout the affected modules. Elevated oxygen concentrations in the presence of an active fire is not a safe practice and can perpetuate the fire and endanger the



crew due to elevated oxygen concentrations around their face mask. To address this risk, fire cartridges have been developed to be used with respirators during fire response.

Over the years that ISS has been in orbit, there has been an increase in orbital debris and therefore, an increase in possible conjunctions with debris. To avoid impacts with debris, it is often necessary to perform a debris avoidance maneuver (DAM). However, there are cases where a possible conjunction is not identified until it is too late to perform a DAM. This has caused ISS crewmembers to take shelter in their Soyuz vehicle twice now (March 2009 and June 2011). If any of the ISS modules were impacted, sheltering in Soyuz vehicles would keep the crew safe in their escape vehicle. Due to lessons learned from the first shelter in place occurrence in March 2009 and valuable feedback from crewmembers, training for this case has been implemented preflight and agreements have been made with our partners regarding the vehicle configuration to reduce risk to the crewmembers in the event of an impact. With shelter in place in the Soyuz, the crew is still vulnerable to impacts to the Soyuz vehicle which they are sheltering in. To reduce this risk, teams are now looking at developing the capability to perform a pre-determined DAM so that in the event of a late conjunction, a DAM can still be performed and move the ISS orbit to one that is free of debris and the threat of impact.

Several other significant updates to emergency procedures are being made, including improvement to depressurization response and toxic spill response. An ISS Emergency Operations team was formed in 2009 in response to an evaluation of emergency procedures prior to increasing the onboard crew complement to 6-person crew. This team is dedicated at improving emergency response on ISS for many years to come.

## **5. EMERGENCY EQUIPMENT**

The initial ISS design called for the placement of a minimum set of emergency equipment, such as fire extinguishers and oxygen breathing masks, in ISS volumes. The quantity and placement of this equipment was largely determined by the size of each module. Operational requirements developed through experience and lessons learned from on-orbit emergency drills have led us to significantly increase the amount of equipment available to the crew, alter equipment locations, and develop new pieces of hardware to improve the safety of the crew and vehicle during emergency response.

Prior to increasing the ISS crew complement from a 3-person crew to a 6-person crew in early 2009, the Safety & Mission Assurance organization performed an assessment of all emergency equipment to ensure adequate quantity and locations of emergency hardware throughout ISS based on occupancy, emergency response procedures, and likelihood of event. Several recommendations resulted from this assessment that were eventually implemented: additional

US Portable Breathing Apparatus (PBAs) would be necessary to ensure safety in depress and fire scenarios, a second ammonia detection kit should be made available to the second Soyuz crew (non-prime crew), additional Russian oxygen breathing masks (ИПК-1М) should be launched to ensure that a minimum of two masks per crewmember are available in case of a need to evacuate ISS (protects for Sokol suit donning in a contaminated atmosphere).

In 2010, all available ground spares of the US portable breathing apparatus (PBA) were launched to ISS to ensure as many masks as possible were available to the crew in the event of an emergency requiring breathing oxygen. The PBAs were placed strategically near the Russian Segment so that if evacuation to the Russian Segment was needed, the crew could bring the extra PBAs with them before closing the hatch separating the Russian and US segments. Earlier this year, certification of the US PBAs for storage and use on the Russian Segment was a milestone and further step towards crew safety by providing more equipment available on the Russian Segment and providing unlike redundancy for the Russian oxygen breathing mask (ИПК-1М).

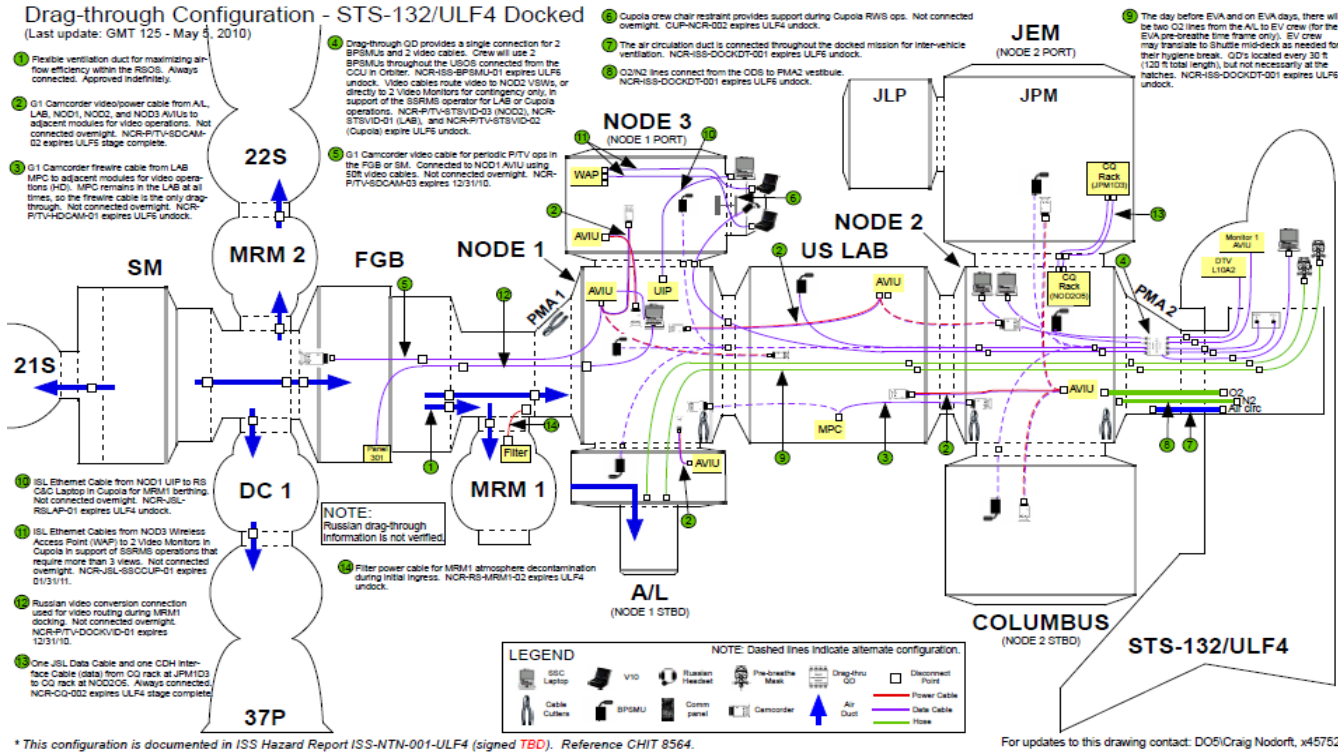
Development of new emergency equipment has also contributed to risk reduction on ISS. In 2006, ammonia response hardware was developed to protect the crew in the event of an internal ammonia leak. Currently in development is a new emergency mask to replace the current ammonia respirators, and is a “one size fits all” design that will allow a crewmember to grab any mask instead of the particular mask they were fitted for, which will improve safety. This mask will also be able to be used in fire response with the addition of filtering smoke cartridges connected to the mask. In response to recommended changes in emergency response for fire to reduce risk to crew and vehicle, fire cartridges were developed to be used with the current ammonia respirators and future emergency mask to be used in place of masks that plug into the ISS oxygen system, which can increase the oxygen concentration significantly in the cabin during fire response, contributing to an unsafe atmosphere. Development of a new fine water mist fire extinguisher is in work to provide more options during fire response and provide unlike redundancy to the current CO<sub>2</sub>-based fire extinguisher. This new fine water mist fire extinguisher will have benefits over the current CO<sub>2</sub>-based extinguisher since discharge of the CO<sub>2</sub> extinguisher requires breathing protection since CO<sub>2</sub> displaces oxygen and in large amounts can be harmful to the crew. Options for portable atmospheric monitoring equipment and thermal cameras are being investigated to further reduce fire response risk onboard.

We continue to evaluate improvements to emergency equipment. Factors such as crew sleeping locations, crew activity level in the different modules, and logistics of emergency response are continually being assessed for emergency equipment placement.

## 6. DRAG-THROUGHS

During operations aboard the ISS until 2009, it was common practice to allow the use of drag-throughs, that is to say, equipment which required cables, hoses, or wiring to cross the threshold of an ISS hatch. Cameras, speakers, ducts, hoses, microphones, computers, lights, and many other devices required the use of drag-throughs. Shuttle missions required extensive use of drag-throughs, especially through the Pressurized Mating Adaptor-2 to Orbiter Docking Assembly hatch. At times there were up to seven drag-throughs penetrating a single hatch. (See figure 3). The Program requirement is that a hatch must be able to be closed and latched in three minutes. Many drag through's could be easily dragged back through a hatch. Some provided quick disconnects on both sides of the hatch interface. Some required the use of cutters, which were to be kept near the hatch. And while the Program felt that the three-minute requirement could still be met, the Program manager became uncomfortable with the proliferation of drag-throughs. The major concern was that during an emergency involving a depressurization event, a toxic spill, or a fire, cutting, disconnecting, or otherwise clearing these hatches could prove problematic. In these less than ideal circumstances we might well violate our three-minute rule. So at the Program Risk Assessment Board in February 2009, Mr. Suffredini gave an action to implement a "no drag-through requirement" and to identify ways to eliminate the current drag-throughs on ISS. Since then, the number of drag-throughs has dropped. Every drag-through now requires an NCR, and those are reviewed thoroughly to assure that there is no other possible means of accomplishing the desired function. There are still drag-throughs on the ISS, but the Program manager has effectively halted their proliferation, and biased designers toward looking for solutions that do not require the violation of hatch interfaces.

Figure 3



## 7. EVA SHARP EDGES

Prior to STS-120/ Flight 10A, there was a rapidly developing concern with respect to out-of-family EVA glove damage observed post-EVA (Figure 1). The concern was of catastrophic significance, as a through-hole in the EVA glove beyond a specific dimensional threshold would result in loss of crew. In some cases, the observed damage had been above or right at the threshold of catastrophic concern, but the damage had always been isolated to the outermost protective layer. The damage never penetrated deep enough to pierce the thin, sensitive pressure bladder layer located just inside the repetitively damaged outermost protective layer, and therefore no leaks to the pressurized suit system had been experienced. At the time, large uncertainties existed as to the possible proximate causes for the glove damage. Open fault tree items ranged from glove workmanship issues to MMOD induced sharp edges on ISS.



Figure 1: STS-120/10A, Right Glove

An “overglove” concept (Figure 2), basically a protective mitt worn over the existing EVA gloves, was prototyped on a highly accelerated schedule in an attempt to support the quickest possible manifesting for interim risk reduction. The overgloves intuitively added an additional layer of cut protection, but the crew had not been appropriately trained to use them... and there were several other concerns with respect to the cumbersomeness of their use. However, the overgloves were used successfully over several EVAs while a more extensive and permanent EVA glove modification was completed.



Figure 2: Overglove shown installed on glove

With heightened priority, a series of glove modification options were rigorously tested and evaluated. The EVA Project Office settled on the addition of a layer of tough “Turtle Skin” material to the affected gripping region of the EVA glove. The recognition of a negative safety risk trend (despite many years of successful performance) and the subsequent effort to provide a more robust EVA glove greatly improved the safety risk posture for all US EVAs. To date, no additional cuts or glove damage have been noted post EVA.

## **8. PLASMA SHOCK HAZARDS**

It was well understood in the initial ISS design concept that the vehicle would be traveling through and interacting with the plasma present in the Earth’s ionosphere, and that this could create buildups of negative charges, and cause undesirable current paths through the vehicle, or arcing to the plasma. Dual PCU’s (Plasma Contactor Units) were provided in the spacecraft

design to ground the vehicle to this plasma environment by discharging streams of electrons. This design feature is particularly important in preventing the potential for charge buildup and subsequent current flow through crewmembers (resulting in potentially dangerous electrical shocks) during EVA's. This capability is further augmented through the operational ability to shunt or feather the solar arrays.

However, as the vehicle configuration matured, another source of charging became apparent: motion of the vehicle through the Earth's magnetic field (particularly near the Earth's poles) caused induced currents to flow through vehicle structure and create both positive and negative potentials that grew larger as the vehicle truss length grew longer. After much discussion, it was agreed that these positive potentials presented a significant electrical shock risk to EVA crewmembers, especially for EVA's requiring operations at or beyond the SARJ (Solar Alpha Rotary Joint) on the Truss. Modifications were made to the suit and to EVA hardware to provide insulation and prevent the EVA crewmember from becoming part of the potential circuit path. It has also been determined that this risk can be completely mitigated by changing the vehicle attitude prior to an EVA, by orienting the ISS with the Truss Segment perpendicular to the Earth (YVV). This reduces the magnetic flux-induced currents through the Truss, reducing potentials to acceptable levels.

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