Practical Applications of Cables and Ropes in the ISS Countermeasures System

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As spaceflight durations have increased over the last four decades, the effects of weightlessness on the human body are far better understood, as are the countermeasures. A combination of aerobic and resistive exercise devices contribute to countering the losses in muscle strength, aerobic fitness, and bone strength of today's astronauts and cosmonauts that occur during their missions on the International Space Station. Creation of these systems has been a dynamically educational experience for designers and engineers. The ropes and cables in particular have experienced a wide range of challenges, providing a full set of lessons learned that have already enabled improvements in on-orbit reliability by initiating system design improvements. This paper examines the on-orbit experience of ropes and cables in several exercise devices and discusses the lessons learned from these hardware items, with the goal of informing future system design.

I. Introduction

The human body experiences several changes after a short period of time in a microgravity environment. For example, the body experiences much lighter loads, resulting in a loss of bone and muscle mass. For crewmembers that remain on-orbit for an extended period of time, the losses of bone and muscle accumulate and crewmembers can begin to experience serious effects. [1]

The National Aeronautics and Space Administration (NASA) uses exercise countermeasures on the International Space Station (ISS) to maintain crew health and combat the negative effects of long-duration spaceflight on the human body. Most ISS exercise countermeasures system (CMS) equipment rely heavily on the use of textile and wire ropes to transmit resistive loads and provide stability in a microgravity environment. For a variety of reasons, including challenges in simulating microgravity environments for testing and limits on time available for life cycle testing, this equipment has experienced a number of on-orbit operational cable failures. As a result, continued ground testing and on-orbit experience since the first expedition on the ISS in 2000 provide valuable data and lessons learned in materials selection, applications, and design techniques to increase service life of these ropes.

This paper presents a review of the development and failure history of textile and wire ropes for four exercise countermeasure systems—the Treadmill with Vibration Isolation and Stabilization (TVIS) System, Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) System, Interim Resistive Exercise Device (IRED), and the Advanced Resistive Exercise Device (ARED)—to identify lessons learned in order to improve future systems. These lessons learned, paired with thorough testing on the ground, offer a forward path towards reduced maintenance time

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and up-mass for future space missions. (Note – The Second Generation ISS Treadmill (also called "T2") is not discussed as it does not utilize ropes as significantly as these devices, and the ropes that are used do not have any failure history.)

II. System Descriptions

The following sections provide a description for each system so as to enable a better understanding of the context of the rope failures and the lessons learned.

A. TVIS

The TVIS system was first deployed in 2000 and provided aerobic conditioning by simulating Earth's gravitational force (1-g) running or walking on a treadmill in the microgravity environment of the ISS. With appropriate loading, treadmill exercise also provided impact forces and maintained neuromuscular and postural mechanisms.

The Vibration Isolation and Stabilization (VIS) System minimized the transfer of dynamic forces caused by treadmill exercise to the structure of the Russian Service Module (SM) and other parts of the ISS, while at the same time maintaining a stable running/walking surface. The VIS components were software controlled and worked in unison to counteract the pitch and roll forces imparted and to provide a flexible mechanical connection to the ISS by stabilizing TVIS against excessive motion caused by exercise. The active components of the VIS System were the gyroscope, four linear slide-mass stabilizers, four motor controllers and a VIS controller. The running surface of the treadmill was used in much the same way as any conventional terrestrial treadmill, except the user was held to its surface by the Series Bungee System (SBS) and/or the Subject Load Device (SLD), which each attached to the Treadmill Harness to counter the microgravity environment. TVIS served on ISS until 2013, at which time it was replaced with the Russian BD-2 treadmill [2]. Figure 1 shows a schematic of the TVIS, while Figure 2 shows the TVIS in use on ISS, including the SBS.

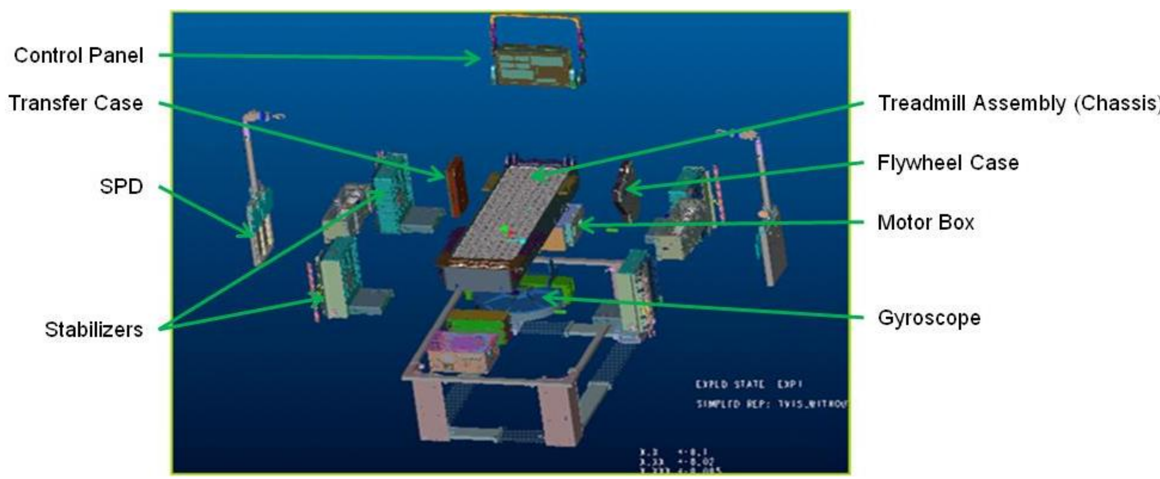


Figure 1. TVIS System.

Figure 2. TVIS in use on ISS.

B. CEVIS

While the TVIS provides the ability to run or walk in microgravity, the CEVIS system provides cycling aerobic exercise, in either a recumbent or upright posture. CEVIS is also used for pre-breathe operations prior to an Extravehicular Activity (EVA), periodic fitness evaluations, and pre-landing fitness evaluations. The CEVIS Ergometer can be controlled electronically via protocols in a control panel, or it can be manually controlled by the subject. The Control Panel displays real-time subject data, including heart rate, speed, and workload. Two Inertial Vibration Isolation and Stabilization Boxes are attached at either end of the Ergometer and provide passive mechanical counter-inertia to the forces imparted by the riding subject. These minimize forces imparted into the CEVIS frame and hence into the ISS structure via wire rope isolators located in each of the four corners. CEVIS was deployed on ISS in March 2001 and continues to be in service. Figures 3 and 4 shows the CEVIS schematic and the CEVIS in use in an upright posture, respectively [3].

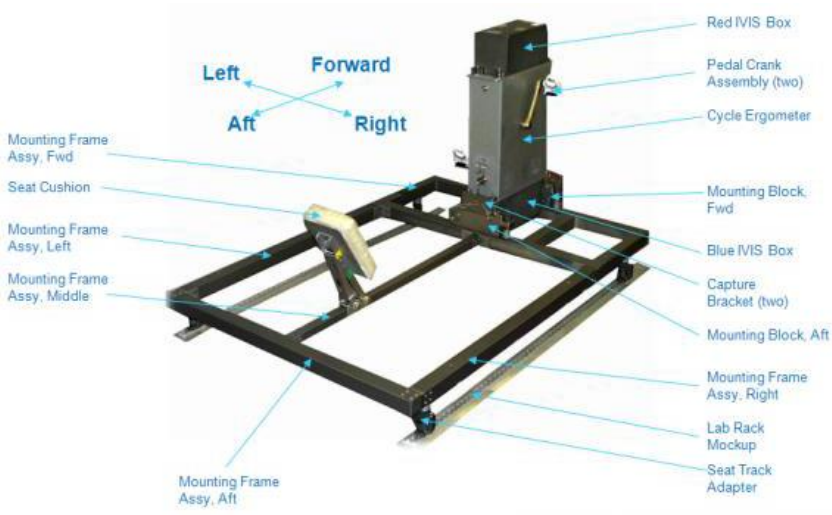
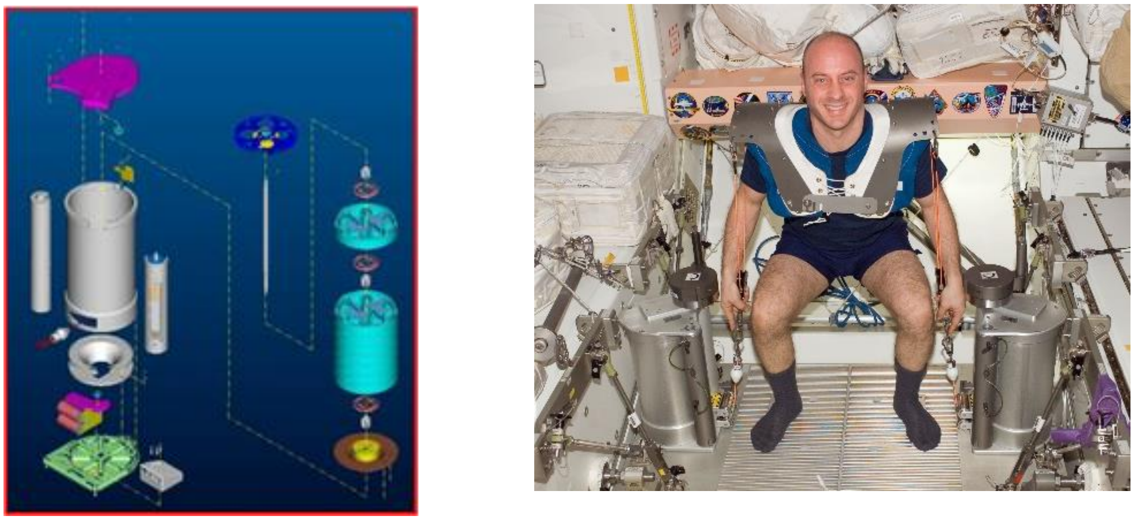


Figure 3. CEVIS System.

Figure 4. CEVIS in use on ISS.

C. IRED

Aerobic exercise is one powerful countermeasure to microgravity effects, but additionally, resistive exercises are needed to prevent both muscle and skeletal atrophy. To provide ISS astronauts an interim resistive exercise capability, the IRED was developed and was in service from May 2000 until ARED was installed in January 2009. It had a capability of 320 pounds of resistive load using two canisters. The canisters contained rubber spring flexpacks, which when rotated about a center shaft, provided resistive load to the user via a rope and pulley system. The load adjustment was created by turning a hand crank and preloading the flexpack stack to the desired load. IRED did not contain vibration isolation features or a capability to record data to verify device performance. Figure 5 shows the elements in the canister used to provide resistance as well as the IRED in use [4].



IRED Canister Exploded View **IRED in use on ISS**

Figure 5. IRED Figures

D. ARED

IRED provided an interim capability until the ARED was ready for use. Today, the ARED is the primary resistive exercise device on ISS, utilizing two vacuum cylinders to provide workload. The ARED system incorporated multiple improvements to the IRED hardware, including increased load to 600 pounds, a more desirable load characterization, vibration isolation, lower maintenance requirements, and greater ease of use and reliability. It provides bar and cable (rope) exercises, much like ground gym equipment, and it contains an inertial flywheel system to simulate the feel of 1-g free-weights. ARED was deployed in January 2009 and continues in service. Figure 6 shows the ARED as it is used on ISS [5].

Figure 6. ARED in use on ISS.

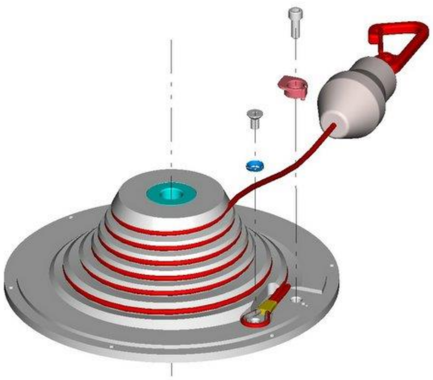
III. Failure History and Lessons Learned

Ropes and cables are used for three purposes on ISS exercise systems: to provide the primary tensile resistance load path, to provide isolation between the exercise system and the ISS structure in a flexion/bending application, and as tethers. This section discusses the failure history and corrective actions for each functional area.

A. Primary Tensile Resistance Load Path

1. IRED

The design for IRED included a spiral outlet pulley to counter the spring constant and provide uniform load, which required a strong, durable, and lightweight cable. Several materials were considered, but the need to have a low-stretch cord focused the search to a few polymer rope options. With Johnson Space Center (JSC) located close to Galveston Bay and the Gulf of Mexico, the sail rigging shops in close proximity became an advantage to the IRED team, as the mechanics of the canister and cord were similar to the rigging of a sailboat. The technicians in the sailing shops were not only familiar with the material properties of certain cords, but they also knew which ones were more durable and best fit the application of the IRED. They shared their knowledge on rope splices and eyelets, proper needle selection for stitching, and whipping techniques to make the cords streamlined and durable. After consulting with the sailing riggers, two candidate cord materials were recommended for evaluation. The first, made of 1/8 inch AracomT®, was tested in the IRED cord life-cycle test rig. This rig consisted of two spiral pulleys, wound with cords attached to bags of lead shot weighing 150 pounds each. This allowed two cords to be tested at a time. The IRED pulleys were coated with Poly-Lube® to prevent corrosion and provide a slick surface, preventing wear and binding on the ropes. The AracomT cord broke at only 6,930 cycles, which was less than a week of cycles for three ISS crewmembers, well below the acceptable threshold of service life. The next cord tested was made of 1/8 inch Edelrid Dyneema®, and it broke at 214,060 cycles, which using a scatter factor of 4, allowed it to be certified to 53,515 cycles with 2-week inspections for damage. (Note: the structural analysis community typically recommends a scatter factor of 4 for structure/safety-critical applications, and a factor of 2 for non-structure/non-safety critical applications). This would allow each cord to be used for approximately 3 months on orbit before replacement would be required, dependent upon the number of crewmembers and their daily usage rate. This was acceptable to the ISS Program, and this cord was selected for the IRED flight design. Figure 7 shows a diagram of the IRED Spiral Cord Pulley along with the cord life cycle test equipment. [6,7].



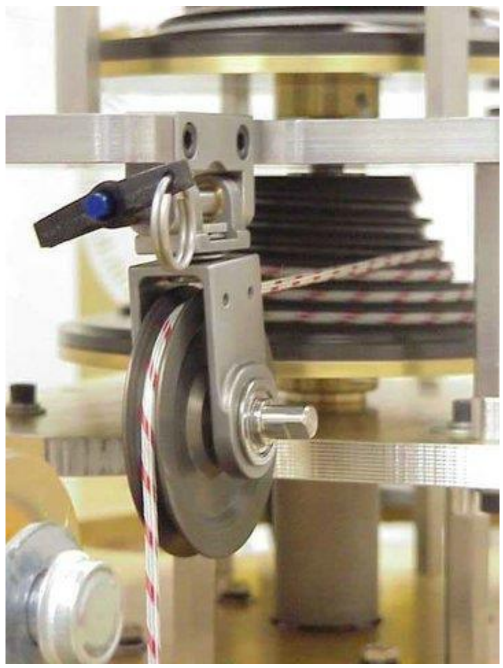


Figure 7. IRED Spiral Pulley with Cord and Life Cycle Testing Support Equipment

Failures of the IRED canister cords led to slight evolutions in the design and insight into how to conduct verifications. A Dyneema cord broke early in the IRED life-cycle testing, raising doubt about the robustness of the design. Confidence was restored when a burr was discovered on a spiral pulley that had been installed into the test rig, which resulted in accelerated erosion to the cord sheath over a short time. Had this pulley been properly inspected, the cord would have reached its expected life. Another failure mode involved premature breaking during proof load testing for a certain batch of canister cords. An investigation uncovered that the number of stitches inserted into splice at the terminal end of the cords was out of specification and that too many splice stitches weakened the cords. The drawing and fabrication procedures were updated to tighten the tolerance on the number of splice stitches, and subsequent batches of cords never experienced this failure again [8,9,10].

2. ARED

ARED has rope failures in two areas: workload ropes, and the upper stop cable. The next sections will address each area, in turn.

a. Workload Ropes

The ARED uses two different types of ropes to achieve workload for the user during cable exercises, the cable arm ropes and the exercise rope. The load on the cable arm ropes is provided by the resistance of the vacuum cylinders through the cable arm and is transmitted to the exercise rope through a series of pulleys and belts. The cable exercise system was designed so that the two cable arm ropes experience a higher load than the exercise rope. The cable arm rope pulleys have a conical profile that the rope winds around. This design mitigates the effective change in length of the cable arm moment arm as it moves through its stroke, which, in turn, maintains a constant load on the exercise rope. The pulleys in the ARED are coated with TUFRAM® to prevent corrosion and provide a slick surface, preventing wear and binding on the ropes. The ropes utilize splicing where the fibers are woven into themselves, creating a friction retention that tightens as forces are applied. Figure 8 shows the ARED rope and pulley system.

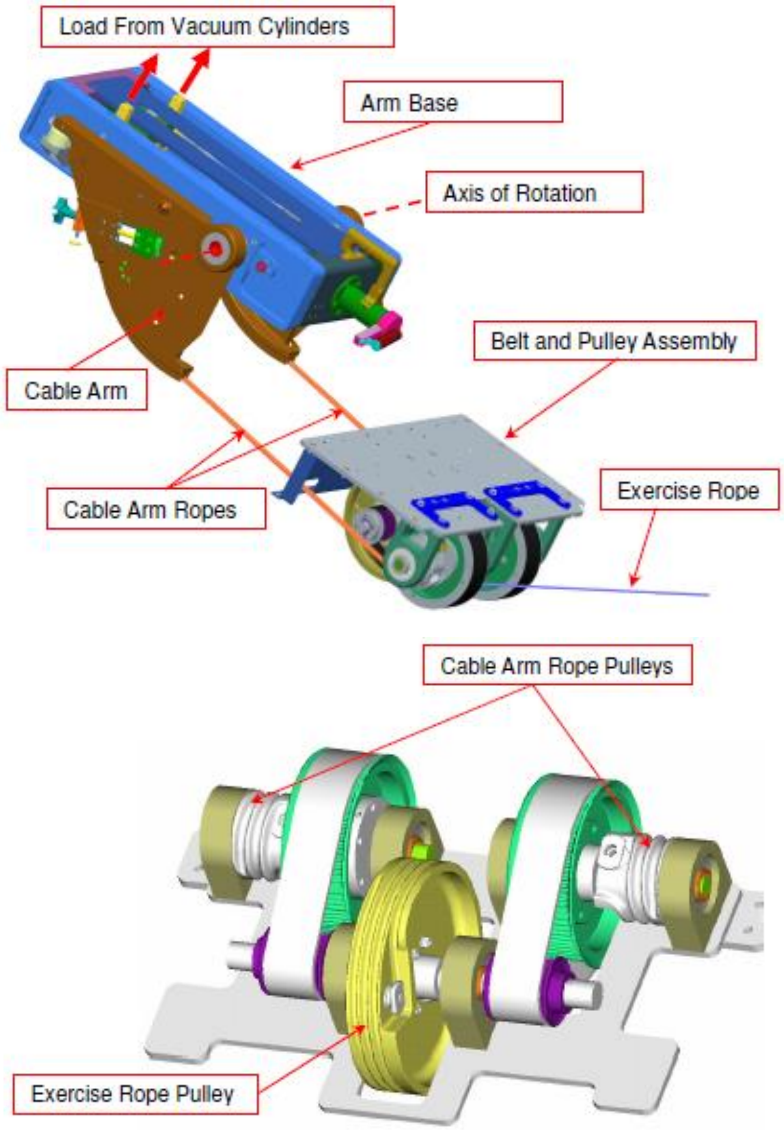


Figure 8. ARED Rope and Pulley System

The initial design phase specified a rope material that exhibited the least amount of stretch possible. After consulting with a local sail rigging shop, the initial rope materials chosen for evaluation were Dyneema and

Vectran®. Dyneema was selected based on the vendor's recommendation and prior experience on IRED. When tested under identical loading conditions, identical lengths of the Dyneema rope stretched 6 inches, whereas the Vectran rope stretched only 2 inches. Even though both materials were found to have similar strength and abrasion resistance, Vectran was chosen for life cycle testing due to the difference in elongation.

The life-cycle testing was conducted on 3/8 inch diameter cable arm ropes and yielded a failure of 138,612 cycles. The 80-inch ropes had breakage about 24 inches from the end near the cam pulley. A broken Vectran rope was submitted to JSC Materials and Process Branch for failure analysis, and the analysis concluded that the failure was caused by flex fatigue and abrasion from the pulleys during the life-cycle testing. Based on the test results and lower stretch characteristics, the Vectran cable arm ropes were certified using a scatter factor of 2 for 69,306 cycles, which was initially projected to last greater than 6 months for 3 crewmembers. Subsuquently, the actual consumption rate was higher, so they currently last approximately 3-4 months for 6 crewmembers. Figure 9 provides a photograph of a failed Vectran ARED Cable Arm Rope after initial life cycle testing.

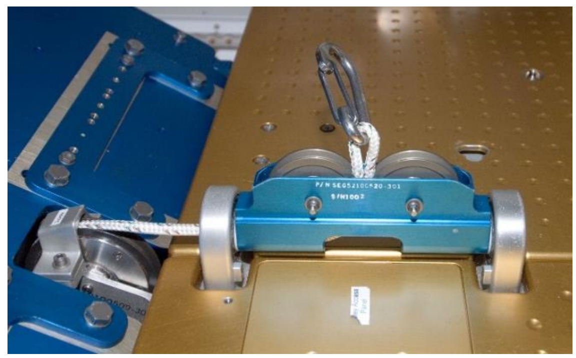
Figure 9. Failed ARED Cable Arm Rope

Due to the success in testing of the Vectran Cable Arm Rope, Vectran was also selected for the initial Exercise Rope life cycle test. The 1/4 inch diameter Vectran exercise ropes yielded a failure at 63,002 cycles. The rope broke about 60 inches from the exit pulley end, the point that travels through the platform pulleys. Based on test results and using a scatter factor of 2, the rope was certified for 31,501 cycles, which would initially last approximately 4 months for 3 crewmembers. Subsuquently, the actual consumption rate was higher, so they lasted approximately 2 months for 6 crewmembers.

After several years of use and significant accumulated maintenance time to change out the exercise ropes approximately every 6 weeks, the ISS Program requested that the team investigate another rope design that would provide longer life between change-outs. Due to the flex fatigue failures seen during tests of Vectran ropes, local sailing rigging shops recommended evaluating a polyester rope for the ARED application. Although polyester stretches more than Dyneema or Vectran, a rope with a polyester core and polyester sheath was believed to be more resistant to flex fatigue than Vectran. A life-cycle test using the 1/4 inch diameter polyester core and polyester sheath rope was conducted, and the new design survived 485,434 cycles without a failure. The design was certified using a scatter factor of 2 to 242,717 cycles, which is equivalent to approximately one year of service life in the ARED. The rope stretched only 2 inches during the initial test phase. The rope was certified, flown, and installed on orbit in July 2011. [11].

Failures of the ARED workload rope led to two improvements in the design. The first failure occurred in the Vectran exercise rope design on ISS. As the rope was cycled over time through the outlet pulleys, the splice grew in diameter due to end (tail) of the rope working its way back through the braid. This caused the splice to wedge in the pulleys and added tension to the system, which caused the cable arms to pop out of the detents during bar exercise. This was corrected by loosening the tension on the cable arm ropes and allowing the exercise rope splice to no longer retract into the pulleys. This issue, along with the short life of the Vectran exercise rope, helped justify the new polyester exercise rope redesign. The second failure of an exercise rope occurred on ISS with the polyester rope. In January 2012 the crew was exercising and noticed that the splice had come apart, rendering the rope unusable. This condition was never observed on the ground during testing, but the possibility of manual manipulation during zero-load conditions of the splice could have caused the splice to come apart, as without load on the rope, the fibers tend to loosen slightly. Based on this failure, the ISS Program and the CMS team decided to stand down on use of the polyester rope on orbit and install the Vectran rope as an interim workaround. After a redesign effort, including consulting with the rope supplier, the team decided to add a lock stitch to the rope splice in order to prevent the splice from coming apart during zero-load conditions. After the design was fabricated, the life cycle test was reinitiated with the new rope design and certified to the same cycle count as the previous polyester rope design (242,717 cycles). The updated polyester rope design was installed on orbit in September 2014 and continues in use currently. The life cycle test continues currently, and as of August 2015, the rope was certified for 481,958 cycles, which equates to approximately 2 years of operational life. Figure 10 provides several images of ARED exercise rope designs and related failures. [12,13]

Vectran Rope Wedged in Pulley



Polyester Rope Installed

Polyester Rope Splice Pull-Out

Polyester Rope With Lock Stitch

Figure 10. ARED Exercise Rope Designs and Related Failures

b. Upper Stop Cable

The second type of ARED rope failure was in the Upper Stop Cable. The ARED bar contains a mechanism that allows it to latch into an upper position in order to perform exercises that begin in a standing position, such as squats and heel raises. A spring actuated pawl swings and latches against a plate fastened to the ARED frame. The crewmember actuates the upper stop mechanism by lifting the bar and changing the angle between the main arm section and the vertical adjustable lift bar slides. The sliding linkage, including the upper stop cable made of Teflon®-coated 1/8 inch wire rope, provides the means for the crewmember to release pawl by changing the angle of the lift bar and the main arm. Figure 11 shows the ARED Upper Stop Actuator Cable Mechanism [5].

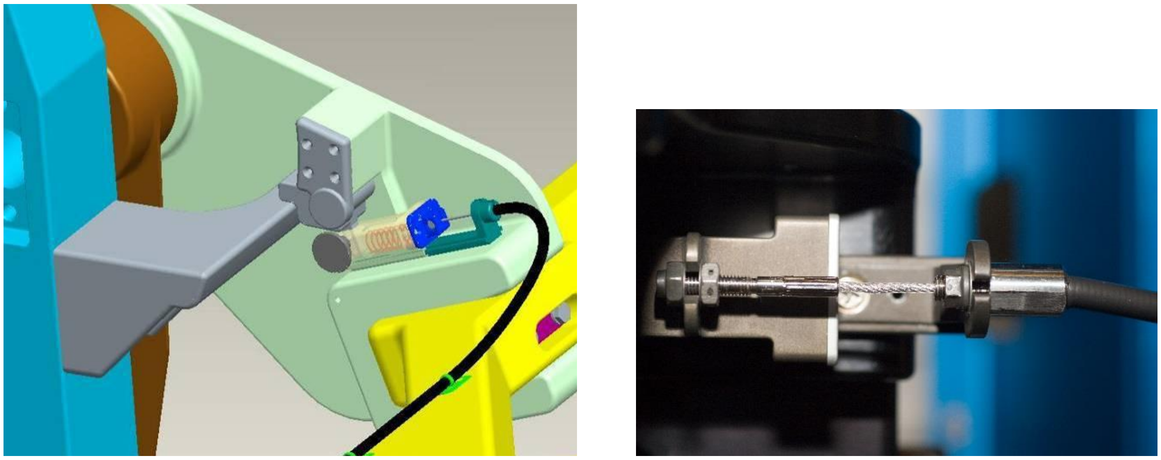


Figure 11. ARED Upper Stop Actuator Cable Mechanism

The upper stop cable has been an area of multiple failures since ARED was put into service in 2009. The failure typically begins as a bent or kinked cable and progresses to a broken or frayed cable, halting all exercises performed from the upper stops. This problem had a history of occurring approximately every 2 years, requiring the cables be replaced with new units, but in late 2014 into early 2015, a series of rapid-succession failures occurred on the upper stop cables on both the left and right sides. This initiated a root-cause investigation, and it was concluded that the mechanics of the mechanism applies a push force on every repetition of bar exercise as the pawl follows the bottom edge of the upper stop plate. However, the forces applied to the upper stop cables were never intended to be push forces. They were only intended to operate in tension. The fatigue resulting from the cycling of this push force eventually causes a kink in the cable, which erodes the Teflon sheath on the cable housing, and eventually causes it to fray or break, halting upper stop exercises until it can be replaced. As a result of the findings, the crew was requested to increase their frequency of inspections, and the engineering team launched additional spares to ISS. A redesign of the upper stop mechanism to eliminate the push forces is currently in work, and life-cycle testing will be used to compare the life of the old and new designs. (Note: There was no life cycle testing performed on the upper stop hardware) ARED Upper Stop Cable Failures on ISS are depicted in Figure 12 [14,15].

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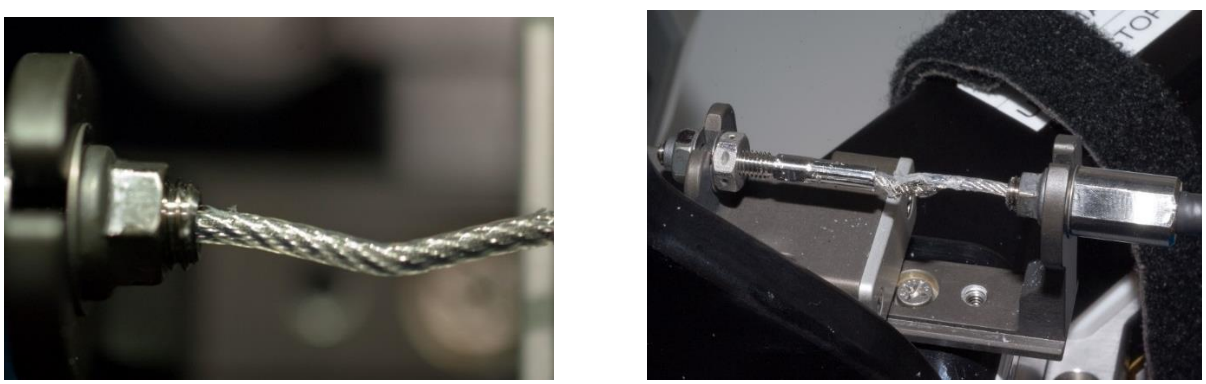


Figure 12. ISS ARED Upper Stop Cable Failures

3. TVIS SLDs

The TVIS SLDs were the primary subject restraint system hardware and were attached to the sides of the treadmill chassis. Prior to exercise, the crewmember would don the TVIS harness, clip the harness y-straps or attach the SBS to the respective end stops on the SLD's cables. The SLD pair provided loading from 40 to 220 pounds, adjustable via control panel entry or protocol. Each SLD was instrumented with a load cell, which measured tension in the cable attached to the subject. The load variation of the SLD is approximately 6 lb/in. of cable extension. In the initial SLD design the cable exited the SLD housing at the top plate from a non-fleeting, fixed position exit pulley. Due to failures discussed in the subsequent section, the pulley was upgraded to fleeting pulley in 2005 due to varying cable angles produced by crewmembers not using the TVIS Subject Positioning Devices (SPDs). The cables on the SLDs were 1/8 inch galvanized steel cable with a nylon sheath Figure 13 shows an exploded view off the TVIS SLD [2].

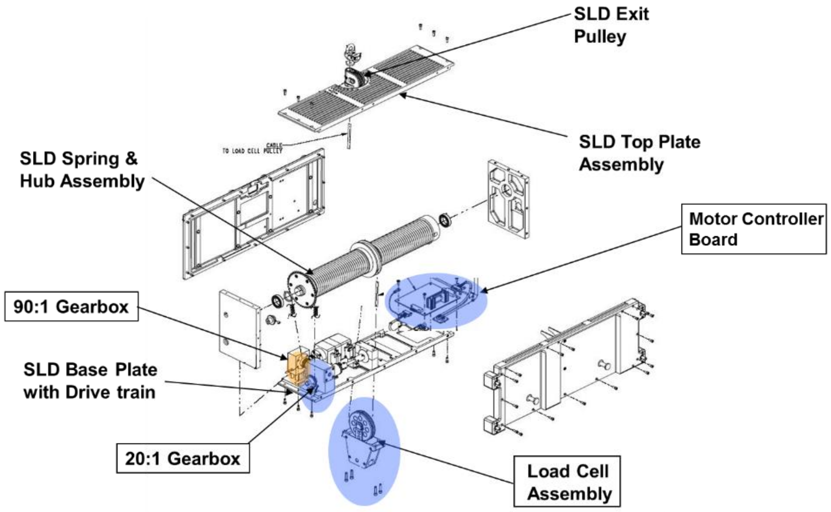


Figure 13. TVIS SLD – Exploded View

The first set of SLDs went into service with the rest of the system in November 2000. On July 30, 2001, the crew reported that the SLD cable nylon sheath had worn away from the wire rope portion of the cable, causing the cable to jam. The root cause was determined to be off-axis cable loading and cable sheath abrasion due to TVIS exercise without the crew using SPDs. Passive exercise caused the subject to lean forward to manually drive the treadmill belt. As an interim workaround, the crew installed the SLD eyebolts and used SBSs for loading as a contingency. New SLDs were flown and installed in December 2001. In March 2002 the crew reported scraping noises coming from the second set of SLDs and noted asymmetric loading between the SLDs. These were removed from service, and again, the SBSs became the backup loading mechanism. A post-flight inspection revealed that exit pulley bearings and load cell pulley bearings had failed. This damage was caused when the SLD cable jumped off of the exit pulley during passive exercise on the TVIS System, again without the crew using SPDs. The bearings were not able to handle the off-axis loads and failed prematurely. In September 2006 the left SLD of the third set of SLDs installed on ISS experienced a failure where the cable end stop detached from the SLD cable during exercise. The cable end stop remained attached to the crewmember's harness, and the free end of the cable retracted into the SLD housing. Visual inspection determined that the wire rope had separated from the ball shank termination that was swaged to it. Suspected causes were failure due to an improper crimp or a material defect, but the failed components were lost in transit from ISS to JSC, so no ground analysis was performed. Additionally, the post-fabrication verification pull test records could not be found by the external vendor. As a result the SLD drawing was updated to include a mandatory inspection point for the post-swage pull test, and all subsequent SLD cable swages were inspected using X-rays to verify proper crimping. A series of redesign efforts and life cycles tests were performed between 2003 and 2009, and changes were made to the SLD design to increase the pulley size, update the bearings, and add a rotating and fleeting exit pulley to prevent off-axis loading of the bearings. A final redesigned SLD was installed on orbit April 23, 2009, and the failures did not reoccur. Figure 14 shows a damaged TVIS SLD cable and the new fleeting pulley design [16,17,18].

Figure 14. Damaged TVIS SLD Cable and Fleeting Pulley Design

B. Flexion/Bending Applications

Exercise systems need to be isolated from the ISS structure to prevent fatigue on vehicle components, and to prevent disruption of science experiments. Wire rope isolators are an effective method of adding isolation to components or even whole systems of the exercise equipment with medium to high cadence (greater than 1 Hertz) activity and movement. The isolators are lightweight, somewhat durable, and require no power to isolate a system during use. The following sections detail the CMS hardware applications utilizing ropes in a flexion or bending method and the associated failure modes encountered during the ISS mission.

1. CEVIS Isolators

The CEVIS isolators are wire rope egg-beater type devices that provide the only structural attachment between the CEVIS frame assembly and the ISS US Lab rack using seat track adapters. They contain 12 strands of 1/16 inch wire rope without sheathing, and an isolator assembly is attached at each of the four corners of the CEVIS frame to minimize the vibrations transmitted from the CEVIS system to the ISS structure during operation. The isolators were not initially assigned a limited life, and they are changed out on an as-needed basis when more than 8 out of 12 wire ropes are severed in a single isolator. The isolators are inspected every 3 months and have had a service life varying from 1 to 3 years. CEVIS isolators used on ISS are shown in Figure 15 [3].

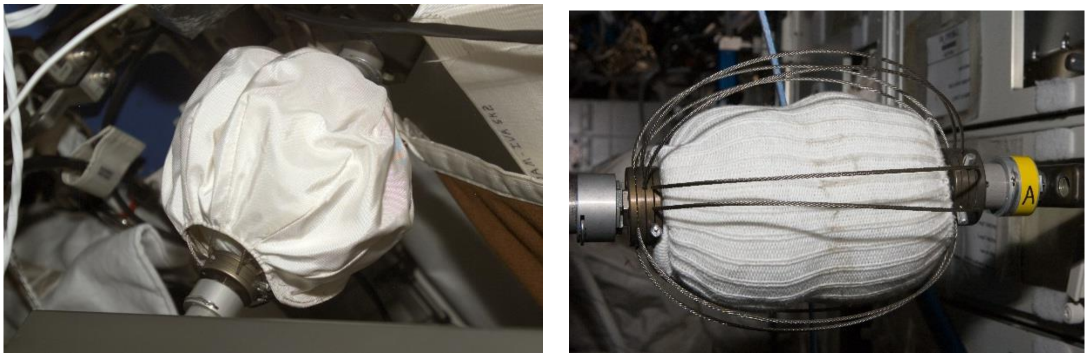


Figure 15. CEVIS Isolators on ISS

Over the service life of CEVIS, inspections are conducted every 3 months to check the status of the isolators. The wire ropes have periodically broken due to fatigue at the clamp point, as a stress concentration exists at that point when the wire ropes are flexed, but they can remain in service if eight or less wires are severed. Once the eighth wire breaks, the unit is replaced. The crew on Expedition 6 added rolled sock-balls inside the wire cage to help reduce movement during the EVA exercise pre-breathe activity, which purges the body of nitrogen before a spacewalk is conducted. This requires rigorous pedaling and movement with the arms, which makes the CEVIS riding very unstable without the socks. They also act as bump stops and prevent severe bending of the wire ropes.

The clamp plates of the CEVIS Isolator were redesigned in 2011 to add a chamfer to the edge of the hole where the wire rope passes through the plates, thus reducing the stress concentration at that point. This small change has increased service life of the isolators substantially, and the true service life is still being evaluated, as only one wire has failed on one isolator in almost 4 years of use. Figure 16 shows the results of a trending spreadsheet tool that documents the number of severed wire ropes of a given set of CEVIS Isolators versus time of service. The graph clearly shows that the new design (magenta lines) is a dramatic improvement [19]. Figure 17 shows the before and after pictures of the CEVIS Isolator design change.

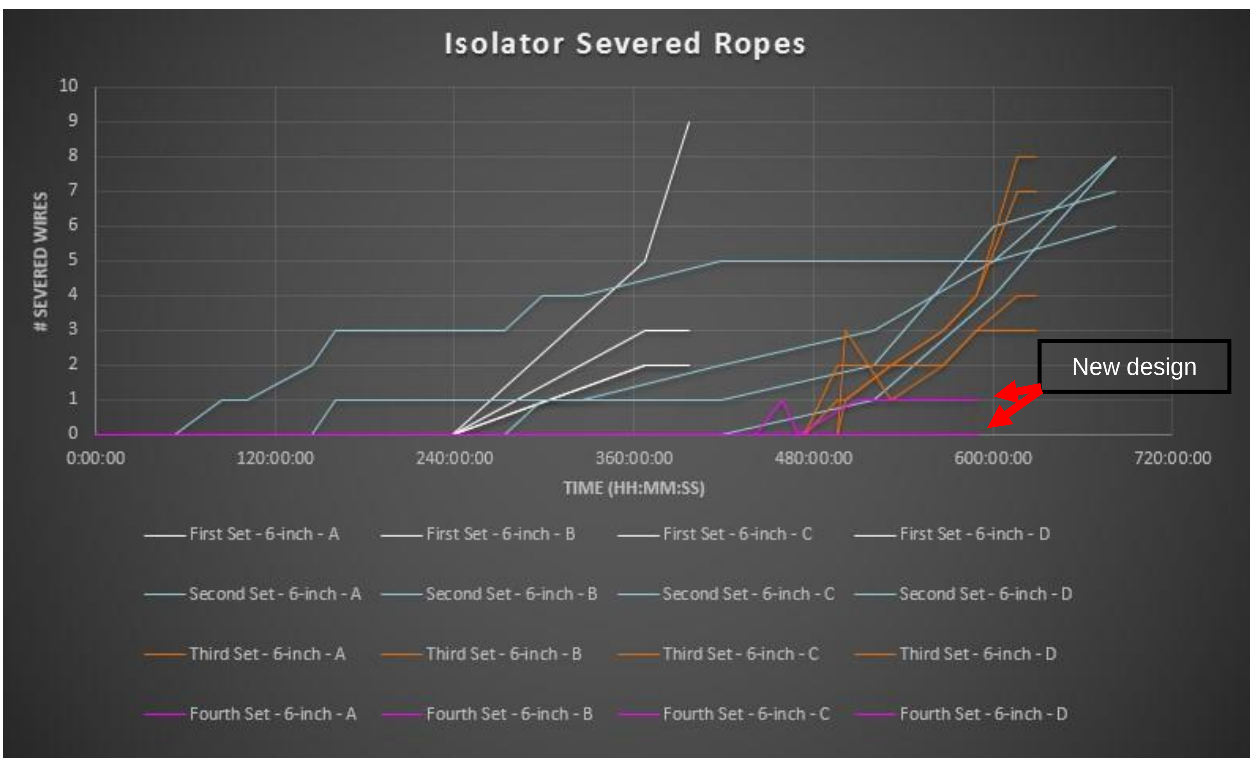
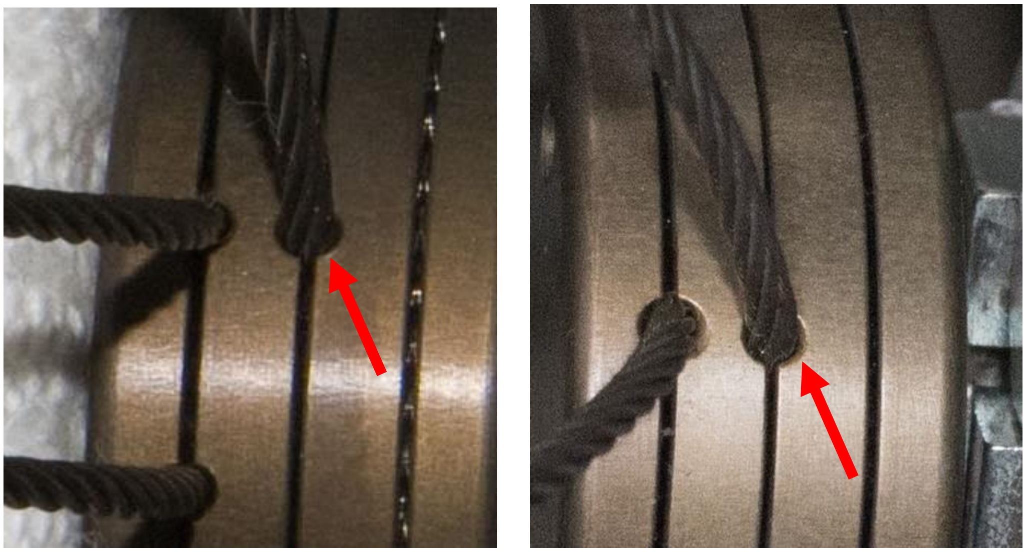


Figure 16. Service life of isolators.



Old design with no chamfer New design with chamfer

Figure 17. Whole edges where wire ropes pass through clamp plates.

2. TVIS Gyroscope Wire Rope

The TVIS Gyroscope Assembly is used to stabilize the TVIS System from excessive roll motion during operation and provides current peak smoothing of the TVIS System power sources. The Gyroscope has a vertical spin axis and pivot bearings positioned in the pitch direction to allow for the required precession during operation. The TVIS gyroscope incorporated two (one per side) 1/8 inch swaged wire rope assemblies that aided in restoring the gyroscope back to its neutral position and prevented excessive movement. The thought was that the wire ropes would act as a spring and dampen out extreme motion before the gyroscope pivots hit the hard stops. The gyroscope wire rope originally was not assigned a limited life, and no spares were launched, but after failures on orbit, a certified operational life of at least 250 hours was derived based on historical data and maintenance inspections. This equated to approximately 9 months with three crewmember use. The gyroscope wire ropes could continue in service past the 250-hour limit if monthly inspections were performed. The wire ropes were required to be changed out, at a minimum, every year. In the event that the gyroscope wire ropes were severed, gyroscope motion increased, resulting in contact with the gyroscope blue rubber bumpers, which acted as the secondary damping system. Once wire rope damage was identified, both wire ropes were replaced prior to resuming TVIS System operations. Figure 18 shows the TVIS gyroscope wire ropes as configured for ISS use [2].

Figure 18. TVIS Gyroscope Wire Ropes

Unexpected damage to the gyroscope wire ropes was first observed in a TVIS treadmill removal and replacement activity in October 2002, about 2 years after TVIS was first operated. Root cause was determined to be a combination of incorrect installation of the clamping plate, which pinched the ropes, and cyclic fatigue due to stress concentrations at the clamp plate. This established a new requirement for a 1-year limited life on the wire ropes. New wire ropes were launched to ISS to replace the damaged ropes, and they were subsequently replaced every year as a maintenance activity. Figure 19 shows a failure of a TVIS Gyroscope Wire Rope [20].

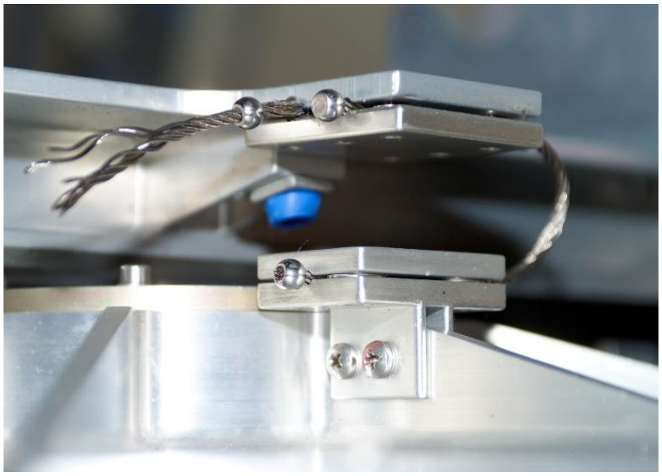


Figure 19. Failed TVIS Gyroscope Wire Rope

3. TVIS Stabilizer Wire Ropes

The TVIS Stabilizer wire ropes centered the TVIS System in the SM pit, provided an attachment point to the SM structure, and isolated forces from being transmitted to the ISS. Each corner assembly contained one textile Kevlar® (later Vectran) stabilizer protection tether and four 1/16 inch steel wire ropes to limit the travel of the movement within the pit. The wire ropes were attached to the TVIS stabilizers via a terminal ball-swage inserted into a slot with a fastened cover plate to retain them. They were mounted on the opposite end in a similar fashion to rails that mounted to the corners of the SM pit. Figure 20 provides a photograph of the TVIS Stabilizer Corner Bracket Assembly including the Wire Ropes.

Figure 20. TVIS Stabilizer Corner Bracket Assembly Including Wire Ropes

The steel wire ropes and Kevlar over-travel protection ropes did not originally have a limited life assigned to them and no spares were stored on-orbit. Damage observed by the crew on Expedition 1 in February 2001 due to the Kevlar stabilizer protection tether severing highlighted the need for maintenance on the ropes. The protection ropes were originally made of Kevlar, but their load rating was below the applied forces on orbit. After a short ground evaluation, the Kevlar design was replaced with Vectran, which had five to six times the break strength of the Kevlar rope, replacements were launched to ISS, and the failure was never observed again. During the same call-down as the Kevlar rope severing, the crew reported that multiple stabilizer wire ropes were damaged or severed. The subsequent investigation concluded that the failure could be contributed to three causes. First, the failure of the Kevlar over-travel protection rope allowed the wire ropes to become taut and experience the full load of the treadmill chassis pulling on them. Second, it was determined that excessive clamp force between the rope clamp assembly and the stabilizer interface deformed the wire rope, causing premature fatigue. Third, the sharp bend radius imposed on the wire rope also caused the failure at the point of greatest cycling fatigue. As a result, spares were launched to ISS, the damaged wires were replaced, and spares were maintained onboard for the duration of the remaining TVIS service. The TVIS Stabilizer Corner Bracket Assemblies were inspected monthly and the wire ropes were replaced when at least half were severed. A redesign was a possibility, but the ISS Program chose to resupply the ropes and change them out periodically when damage was observed. After the Vectran over-travel protection rope was installed, stabilizer wire ropes typically lasted ~3 years between change-outs. A failed TVIS Stabilizer Corner Wire Rope is shown in Figure 21 [21,22].

Figure 21. Failed TVIS Stabilizer Corner Wire Rope

C. Tethers

Another application of wire ropes on ISS is the use of tethers to retain push-in-place (PIP) pins that are often removed from the hardware assemblies. These pins retain parts that need to be moved, adjusted, or folded. These tethers are typically made from 1/16 inch stainless steel wire rope material with a Teflon sheath, and they keep the pins from floating away in the microgravity environment, as a pin could be lost and the hardware rendered unusable. Examples of these PIP pins include the main arm pins that allow the ARED bar to be adjusted up or down to fit different heights of crewmembers, the VIS pins that lock the ARED VIS in place while the device is not being used, and the ARED hard stop pins that prevent retraction of the upper stop pawls in the deployed position to prevent the bar from going below the stops. The upper stop pins are a control for an identified in-flight hazard where the crewmember could potentially be injured by the bar during heel raises, which is typically the exercise performed under the highest loads [5].

1. Main Arm PIP Pin

Crew reports in 2011 indicated that the main arm PIP pin tethers had frayed Teflon sheaths, but the underlying stainless steel wire ropes were intact. The crew was instructed to wrap the damaged area with tape to prevent potential sharp strands from coming in contact with crewmembers' hands. The root cause could not be determined, but the most likely scenario, which has been observed in crew videos, is damage incurred during rotation of both main arms, instead of one at a time. When one arm is flipped, the pin can be observed and moved out of the way of being pinched between the main arm and slider track. When both arms are rotated simultaneously, the pins cannot both be observed, and pinching can occur, causing damage to the tether. The crew is trained to do single rotations and is aware of the damage that can occur. Spare tethers are on board the ISS in case replacement is required [23].

2. VIS PIP Pin

Crew reports in 2012 indicated that the VIS PIP pin tethers had frayed Teflon sheaths, but the crew did not think the damage required tape to protect them from sharp frayed wire strands. The root cause could not be determined, but the most likely cause was the tethers being pinched between the pin and the VIS outer plate due to the pins not being temporarily stowed in the provided stowage slots when not inserted into the VIS. This would allow the pin to float and become pinched during ARED exercise. The crew was trained to temporarily stow the pins when not inserted, and spare tethers are on-board the ISS in case replacement is required. Figure 22 shows a damaged ARED VIS PIP Pin Tether [24].

Figure 22. Damaged ARED VIS PIP Pin Tether

3. ARED Hard Stop Pins (Heel Raise Pins)

Crew reports in 2013 indicated that the ARED hard stop PIP pin tethers had frayed Teflon sheaths and wire. The crew was instructed to wrap the tethers with tape to protect them from contacting sharp, frayed wire strands with their hands. The root cause could not be determined, but the most likely cause was the tethers being pinched between the hard stop mechanism and upper stop plate. This can occur when the pins are not temporarily stowed in the provided stowage holes when removed from the upper stop mechanism. This allows the pin to float and become pinched during ARED exercise. The crew was trained to temporarily stow the pins when not inserted, and spare tethers are on board the ISS in case replacement is required [25]. Figure 23 shows a damaged ARED Hard Stop Pin Tether.

Figure 23. Damaged ARED Hard Stop Pin Tether

IV. Analysis

Given the critical need for ISS exercise systems to remain functional to protect crew health, on-orbit failures are treated with utmost urgency by the CMS project team. In addition to failure root cause analysis and redesign, failures are examined at the aggregate level to identify overall trends. These trends provide a basis for lessons learned, and the application of these lessons learned have resulted in success stories.

A. Lessons Learned Summary

1. Primary Tensile Resistance Load Path

Studying the failure history of ropes and cables used by CMS hardware identifies correlations in the failure modes, and using these lessons helps engineers to design future hardware with more durability and less maintenance time. Textile and wire ropes used in tension as load-bearing paths of resistance must have proper stitching and splicing at the terminal end to survive the harsh conditions of exercise operations. The cables, ropes, splices, and stitching must be tested on the ground using conditions mimicking those on the ISS, including a realistic load profile and hardware configuration, to accurately determine the limited life of the design. This prevents any variables from skewing results and allows the system to maintain the correct number of spares onboard to minimize down-time. Even with the knowledge gained by testing, the failures should be mitigated by pre-positioning spares onboard to minimize down-time, designing the hardware to allow on-orbit maintenance and replacement of limited life components, and involving experienced operational stakeholders during operational concept development to ensure the assumptions and requirements are valid. It is a safe assumption that the ropes will be used outside of the concept of operations envisioned by the designer and stakeholders.

Matching material properties to the system application is also imperative to provide a durable design. Industry experts with experience in similar applications can provide valuable advice on materials selection, termination design, and help in matching pulley selection to the ropes used in the application. Pulley design and workmanship quality are crucial to the success of a rope performing to its full potential. Rope life is significantly reduced by rough surfaces on a pulley or a pulley that is not matched to the proper bend radius of the rope selected. Again, consulting with the vendors and industry experts can help guide the designers to proper application of a design. Also, designing adjustability into the pulley system can accommodate variability in rope length and stretching. Researching and consulting with these experts at the beginning of a project can save considerable time and money due to not having to perform redesign and retest activities.

Finally, workmanship testing performed by an external facility should have some oversight in the form of mandatory inspection points. These inspections ensure the test is being conducted properly and that all test requirements are being met. Factoring all of these lessons learned into the engineering process and allowing sufficient margins for the hardware and spares kept on orbit will allow the system to remain functional for a greater percentage of time.

2. Flexion/Bending application

Wire rope failures used in a flexion/bending application in VIS and other applications in the CMS hardware have been less predictable than the ropes and cables used in delivery of resistance loads. Cycle counts have been collected for resistive loads on systems like IRED and ARED, but vibration isolation systems do not experience predictable cycles, as they are highly dependent on the dynamic conditions imparted by the user and the exercise technique. The only way to mitigate failures of wire ropes used in these applications is to design the systems for on-orbit maintenance and replacement of these limited life components and to provide a conservative quantity of pre-positioned spares onboard to protect for unexpected failures. Additionally, understanding the exact forces and bend radius during use is imperative to selecting the proper rope for that specific application. For instance, had a push-pull wire rope been selected for the ARED upper stop cable, the design would most likely be more durable and a redesign would not be required. An important correlation can be drawn in the failure modes of the CEVIS isolators, TVIS stabilizer wire ropes, and the TVIS gyroscope wire ropes. They all had premature, cyclic fatigue failures at the interface where the ropes and the retaining plates connected. Not only were all of these items certified without a limited life with no life-cycle testing, but they all had clamping plates with relatively sharp corners at the interface. Had these corners had a larger radius with a smoother transition to the bending point and less deformation due to the clamping force, they likely would have had a longer service life.

3. Tethers

The service life of wire rope tethers cannot be accurately predicted, as the life depends highly on crew usage practices. The failures of the tethers can be mitigated by training the crewmembers to stow the pins properly when they are not inserted. Every failure of a PIP pin tether on the CMS hardware since the ISS mission started has been due to pinching and crushing of the tether between moving parts on the hardware. Keeping spare tethers on orbit ensures that the PIP pins are not lost or misplaced, as the tethers can be replaced when damage is observed and before complete failure occurs. Designing hardware that has temporary storage locations available when critical pins are not inserted will help reduce dependency on tethers and lessen the potential for damage to the tethers.

B. Success stories

These failures with their analysis and redesign activities have led to significantly improved performance that can be leveraged for future applications. For example, the ARED polyester exercise rope has greatly reduced the amount of maintenance required to change out the rope, as it has been in service for over 2 years and still shows no sign of wear. The design of this rope will be considered for future long-duration spaceflights if the need for a load-bearing rope is required. The ARED cable arm ropes require a more frequent replacement, but their record of successful use is flawless. They have never failed while in service, and the failures in the life-cycle test rig on the ground have been consistent. The CEVIS isolator design has been reliable and durable after the chamfer was added to the clamp plate holes. This reduced the stress concentration on the wire ropes, and they have been in service for almost 4 years with only one wire severed on one isolator assembly. Given the trend of the prior design, they should continue to be in service for a number of years going forward. These successes would not have been possible without studying previous failures and making slight modifications to improve the durability of the systems as a whole.

V. Conclusion

As human crews embark on long-duration space missions, CMS equipment will be critical to mission success, aiding both crew overall health and their ability to execute specific mission tasks. Use of both textile and wire ropes will certainly find a place in the designs due to their light weight and durability.

Long-duration space missions beyond Earth orbit present a new challenge to CMS equipment – the inability for responsive replacements of failed elements. Systems designed for these missions must be highly reliable and available. Similarly, large quantities of on-vehicle spares will not be feasible due to mass and volume limitations. As a result, designs will need to leverage use of new materials technology and testing to provide predictable failure modes of the ropes. Mechanisms that allow adjustability in rope length due to stretching would enable ropes to be utilized for longer periods of time, and instrumenting the VIS systems, if required, would allow better predictability of failures. Eliminating or avoiding pinch points or possibly designing retractable tethers would reduce wear and increase life, and exploring non-metallic solutions for tethers and isolators could provide innovative designs in these applications. Finally, the most important lesson learned from the history of the ISS CMS hardware is that testing is paramount in predicting failures of ropes or cables. A properly designed test simulates authentic conditions and can be repeated to establish trends in performance to allow confidence in the hardware. A universal test rig that could be modified or adjusted to accept different ropes, cables, and pulleys would be a great asset to future design evaluations for the entire NASA agency. Ropes and cables have been an important part of keeping our ISS crewmembers healthy, and using the lessons learned in future designs, the new generation of CMS hardware will be more reliable and require less effort to maintain.

Acronyms

ARED	Advanced Resistive Exercise Device
CEVIS	Cycle Ergometer with Vibration Isolation and Stabilization
CMS	Countermeasures System
EVA	Extra-Vehicular Activity
IRED	Interim Resistive Exercise Device
ISS	International Space Station
JSC	Johnson Space Center
NASA	National Aeronautics and Space Administration
PIP	Push-in-Place
SBS	Series Bungee System
SLD	Subject Load Device
SM	Service Module
SPD	Subject Positioning Device
TVIS	Treadmill with Vibration Isolation and Stabilization
VIS	Vibration Isolation and Stabilization

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[i] Note – most/all of these references are not publically available. Depending on the specific conference and sponsor, these references may need to be either deleted or incorporated into the text.