International Space Station Crew Quarters On-Orbit Performance and Sustaining Activities

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The International Space Station (ISS) Crew Quarters (CQ) is a permanent personal space for crew members to sleep, perform personal recreation and communication, as well as provide on-orbit stowage of personal belongings. The CQs provide visual, light, and acoustic isolation for the crew member. Over a 2-year period, four CQs were launched to the ISS and currently reside in Node 2. Since their deployment, all CQs have been occupied and continue to be utilized. This paper will review failures that have occurred after 4 years on-orbit, and the investigations that have resulted in successful on-orbit operations. This paper documents the on-orbit performance and sustaining activities that have been performed to maintain the integrity and utilization of the CQs.

Nomenclature

cm	=	centimeter
CQ	=	Crew Quarters
GLA	=	General Luminaire Assembly
ISS	=	International Space Station
JSC	=	Johnson Space Center
kg	=	kilogram
m	=	meter
NASA	=	National Aeronautics and Space Administration
SRAG	=	Space Radiation Analysis Group
TeSS	=	Temporary Sleep Station
USOS	=	United States On-orbit Segment

I. Introduction

The International Space Station (ISS) Node 2 United States On-orbit Segment (USOS) is the home of four Crew Quarters (CQs) designed as the sleeping quarters for crew members during the duration in orbit. Each CQ provides a personal, private location for crew members to sleep, relax, and call home during their stay on the ISS. The CQ was designed with an inividual ventilation system, acoustic mitigation materials, laptop connections, and internet connection to allow crew members personal communication with family and friends. Since their deployment in 2008, the CQ performance has been closely monitored to validate that the design continues to meet requirements. Throughout the last 4 years, minor issues were discovered due to the on-orbit environment, and modifications were made to the existing CQ outfitting to provide additional crew safety and comfort. This paper discusses the on-orbit performance, specifically reviewing the ventilation systems, mechanical issues, acoustic blanket cleanliness, and the incorporation of additional radiation protection.

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II. Overview

The CQ provides 2.1 m^3 of interior volume equipped with radiation protection, acoustic absorbing materials, light, ventilation, laptop power, and internet connections[1] (see Fig. 1). Designed to accommodate crew members for long-duration spaceflight, the CQ has a large amount of attachment points to allow crew members to personalize their sleeping quarters during their stay on the ISS.

Figure 1. CQ on-orbit exterior view (left) and interior view (right).

The structure is divided into three main areas: bump-out, rack, and pop-up. To maximize the amount of interior volume, the bump-out and pop-up were designed to contain key features for operation as well as provide additional headroom. The bump-out houses the ventilation system and is comprised of aluminum panels covered in acoustic absorption blankets. The ventilation system provides airflow at three different speeds, allowing crew members to adjust airflow to their preferred settings. The rack structure is comprised of carbon fiber composite panels on the sides and bottom of the CQ. The back and pop-up of the structure were built with ultra-high molecular weight polyethelyne to provide radiation protection. A detailed CQ overview can be found in previously published papers (see references).

The interior and exterior structure is covered with acoustic blankets that mitigate sound absorpotion into the CQ volume, allowing crew members a quiet environment for personal use. The interior blankets consist of a quilted configuration of Gore-Tex®, kevlar felt, and Nomex®. The exterior blankets consist of a quilted configuration of Gore-Tex®, BISCO®, durette felt, and Nomex®. Adjustable lighting is provided for the crew member by the General Luminaire Assembly light, which uses fabric shades to allow for additional adjustability.

III. On-Orbit Performance

A. General Performance Overview

Overall, the crew members that used the CQs while on the ISS indicated that they are habitable and provide a good volume for performing most day-to-day operations. The crew uses the CQs primarily for sleeping, but also for performing tasks such as donning/doffing clothing, using laptops, private communication, and some minimal personal hygiene. The crew has minimized the amount of eating and drinking that is done in their CQs, mostly to maintain the cleanliness of the CQ acoustic blankets. When compared to the Russian sleep stations and the Temporary Sleep Station (TeSS), the crew indicated that the CQs are quieter and, generally, the crew members could not hear other crew members outside the CQ when the doors were closed. The CQ provides the crew members a private, quiet environment for sleeping. Although the CQs are considered dark enough for sleeping, the lights in Node 2 are turned off during sleep periods.

In general, crew comments indicated that the CQ acoustic blankets have no noticeable odors emanating from them and that the Velcro® attachments were not worn and all were still usable for stowing personal items. Crew members made comments that the CQ acoustic blankets have a few small visible stains but nothing significant.

Crew members like the Velcro® attachment points and the bungee attachments inside the CQ volume for stowing personal items such as pictures and clothing.

For airflow adjustability, the CQ provides a fan speed switch and adjustable guide vanes to allow the crew to customize the airflow levels and direction inside their CQ for crew comfort.[1] The crew reported that, in general, the variable fan speeds and guide vanes provided good adjustability although most crew members set the fan speed and the guide vanes to direct air in one direction and leave them in that position. Nominal fan speed varied from crew member to crew member, but most crew members reported that the fans were kept on medium or high speed the majority of the time. Some crew members commented that fans on high speed produced too much noise inside the CQ. Most crew members felt that the fan low speed did not provide enough airflow and, due to dust accumulation over time in the CQ ventilation system, the fans at low speed produced a low airflow situation that resulted in caution alarms in CQ. The following section describes the specific details of the ventilation system performance.

B. Ventilation System

1. System Operation

Instead of using the Node 2 Common Cabin Air Assembly or the ISS fluid loop connections, the CQ pulls in cabin air from Node 2 for ventilation. The CQ ventilation system utilizes a push-pull fan system, where Node 2 cabin air is pulled into the CQ with the fan located in the intake duct, pushed into the CQ interior volume, and a second fan in the exhaust duct pulls air out through the CQ exhaust vent. This flushes carbon dioxide concentrations and provides heat exchange for crew comfort. Since the majority of noise generated in the CQ is due to the ventilation system, foam and fabric abatements are used to provide noise mitigation. As previously mentioned, the crew members are able to adjust the fan speeds to low, medium, or high based on their comfort and sound levels. Since the main concern with the ventilation system is high carbon dioxide concentration, sufficient caution and warning is built into the system to notify crew members if one or both fans should stop working. Sufficient airflow for removal of carbon dioxide can be accomplished with just one fan operating. The intake and exhaust ducts each contain airflow sensors, as well as a built-in tachometer circuit that reports if the speed and rotation of the fans is off-nominal. If either of the intake/exhaust airflow sensors or intake/exhaust fan tachometer is operating outside the design setpoint, a “1 Fan Failed" alarm is generated. If one component in both the intake and exhaust ducts are operating off-nominally, then a “2 Fan Failed” alarm is generated. The current technology does not distinguish the failure alarm between the tachometer or the air flow sensors. Therefore, it is not possible from the fault signal to determine whether fan speed or low airflow is the cause of the failure. As well, during a “2 Fan Failed” alarm the crew can not continue nominal on-orbit operations in the CQ because there is no guarantee that the CQ ventilation system is providing adequate airflow to prevent carbon dioxide buildup in the CQ volume.

2. Failure and Assessment

Throughout the last 4 years, several fan failure alarms have occurred. The first alarm ("1 Fan Failed") was generated in July 2009 by the starboard CQ, just 6 months after being deployed. The alarm re-annunciated in September 2009. In both instances, the crew removed blockage from the exhaust inlet inside the CQ, which mitigated the alarm. After these events, the caution alarm continued to annunciate intermittently with no identified or reported blockages. In October 2009, the first sustainable "1 Fan Failed" alarm was generated when the fan speed was set to low. Increasing the fan speed proved to clear the alarm. As a result of this indication, troubleshooting was performed to determine the cause and resolve the issue. The alarm was silenced on ISS and monitored by the ground flight control team. As well, the crew continued to occupy the CQ since the one-fan failed state is not considered a crew hazard per the previously established safety flight rule.

The crew was tasked to record airflow measurements in the starboard and port CQ. Measurements were taken at the intake duct outlet and the exhaust duct outlet as seen in Fig. 2 and Fig. 3 using a Velocicalc® ventilation meter. More variablity in air speed readings than expected was experienced due to positioning of the instrument, complexity of CQ flow field, air turbulence, and low range of instrument capability. Although solid conclusions could not be made, general conclusions could be extrapolated. The data indicated that the fans were outputting acceptable airflow rates; however, the airflow in the starboard CQ seemed degraded when compared to the port CQ. As a result of this troubleshooting, a detailed CQ fault tree was developed and all possible failures identified. These included: 1) System effects that are causing the airflow sensor to sense low flow (such as foreign object damage); 2) Airflow sensor hardware has been degraded/damaged; or 3) Other system effects such as a failure of the CQ power supply. As the CQ team conducted the failure investigation, the leading candidate for the cause of this anomaly was dirt/dust buildup on the air flow sensors, which would require increased air flow to prevent the alarm from occurring.

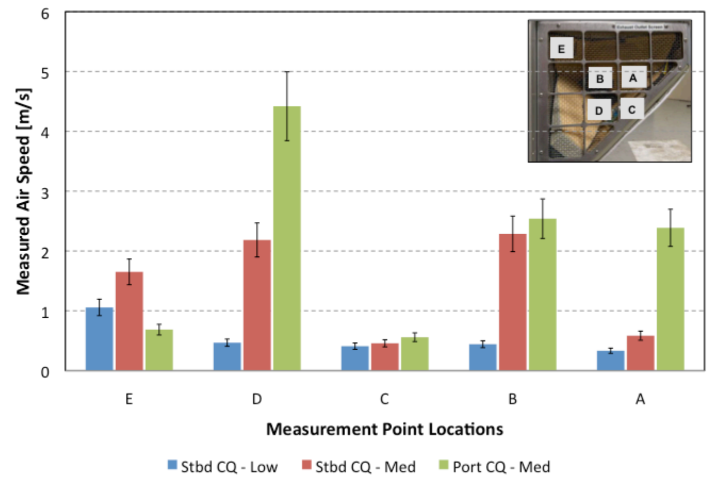

Figure 2. CQ on-orbit exhaust duct outlet air speed measurements.

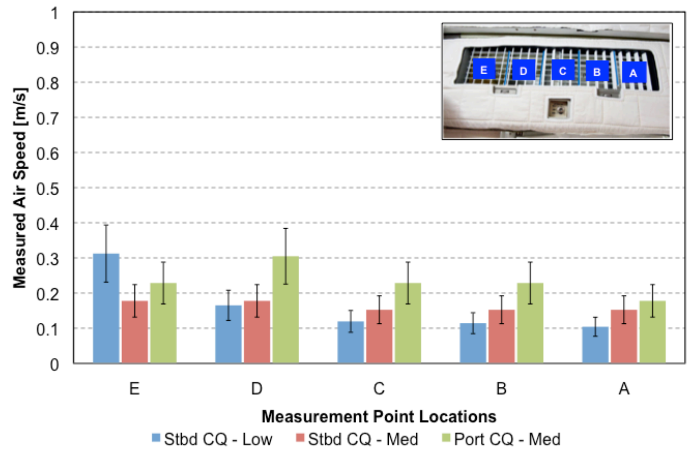

Figure 3. CQ on-orbit intake duct outlet air speed measurements.

3. Recommendation

The CQ team recommended a forward plan to perform a cleaning of the starboard CQ to troubleshoot the anomaly. In November 2010, the starboard cleaning tasks were performed on-orbit. The first step was to determine the location of the failure (intake or exhaust duct) by placing a Ziploc® bag over the exhaust airflow sensor. Covering the exhaust airflow sensor would prevent airflow from reaching the sensor and would cause a “2 Fan Failed” alarm if the anomaly was due to a failure in the intake duct. The test did not result in a “2 Fan Failed” alarm and, therefore, the team concluded that the “1 Fan Failed” alarm was the result of a failure in the exhaust duct. Cleaning of the exhaust flow sensor and exhaust fan area was conducted. Once the cleaning was complete, the CQ was powered back on and the alarm had cleared. However, a few minutes later, another “1 Fan Failed” signal was received and did not clear at any fan speed.

Based on the results of the fault tree assessment and the cleaning task, the CQ team recommended a thorough cleaning of the starboard CQ. Thoroughly cleaning the duct areas (intake and exhaust) of the starboard CQ would aid in further identification of the actual cause of the anomaly. If cleaning of these areas did not clear the anomaly, CQ hardware failures would be investigated further as possible causes. In July 2011, cleaning of the exhaust duct including the fan and the acoustic abatements was performed. Several minutes after the CQ was powered back on, the alarm re-annunciated. The next step was to perform a cleaning of both the intake and exhaust ducts. It is important to note that the intake should be cleaned prior to cleaning the exhaust. Cleaning the exhaust first would be inefficient and likely ineffective since the dust will continue to be pushed into the CQ volume and would travel through the exhaust vent. By cleaning the intake first, the air traveling through the intake duct into the CQ volume and exhaust duct is cleaner, resulting in a more effective cleaning. In September 2011, both ducts were cleaned. The crew photo documented the areas before and after cleaning. They commented that there was a significant build-up of dust on the abatements, flow sensors, and duct surfaces, as photographed in Fig. 4 and Fig. 5. After this thorough cleaning, the fans were set to low speed and the “1 Fan Failed” alarm did not re-annunciate.

Figure 4. Starboard CQ intake air flow sensor (pre- and post-cleaning).

Figure 5. Starboard CQ intake duct (pre- and post-cleaning).

Based on the significant amount of dust accumulation on the sensors, abatements, and fans located in both the exhaust and intake ducts, it was recommended that cleaning of both duct systems be conducted on a regular basis. Regularly scheduled cleaning activities to clean the CQ duct systems have been included in the ISS Preventative Maintenance Assessment, recommending that the intake and exhaust ducts be cleaned every 9 months.

In addition to the starboard CQ, alarms have annunciated in the remaining three CQs. The port CQ “1 Fan Failed” alarm annunciated in September 2010, 21 months after being deployed, and then again in January 2012. In December 2010, a “1 Fan Failed” alarm was generated in the deck CQ, 15 months after deployment. The alarm was intermittent and occurred again in June 2011 but was not sustained. The port CQ and deck CQ have been cleaned since and no alarms have annunciated.

In April 2011, a “1 Fan Failed”caution alarm was generated in the overhead CQ, just 12 months after deployment. Since this was only a “1 Fan Failed” caution, the crew continued to occupy the CQ per the established flight rule. During this time, the crew also noted that the fan in the overhead CQ was noisier than the other CQs. Audio analysis conducted by the crew between the starboard and overhead CQs indicated that the noise source was the exhaust blade pass frequency and harmonics. A month later, a “2 Fan Failed” warning alarm was generated. The failure occurred when the fan was on low or medium and cleared when the fan was on high. The overhead CQ exhaust duct was cleaned in June 2011 and the alarms cleared but re-annunciated intermittently a few days later. However, audio analysis post cleaning indicated improvement in the exhaust fan acoustic emissions. It is believed that the additional dust and foreign object damage accumulated on the fan blades and caused the blade pass frequency to alter slightly. This small alteration can greatly affect the acoustics within the duct system and therefore increase overall noise inside the CQ. The intake duct was cleaned in August 2011..After cleaning the intake duct the CQ was powered back on and the alarms did not reannunciate at any of the fan speeds (low, medium or high).

Currently, all four CQs are performing nominally. The scheduled cleanings (every 9 months) have been effective at removing dust buildup, thus preventing alarm generation. Although cleaning the CQ can take between 3 to 5 hours to complete due to the complexity of the ventilation system, it has been evident that it is effective at removing dirt and preventing alarms. Additionally, cleaning of the exterior mesh intake and exhaust screens on a weekly basis has reduced the dust and debris buildup (through observation). The CQ project team and the ISS community can take away several lessons from this anomaly and these troubleshooting procedures. This issue was not expected during the development of the CQ. The on-orbit airborne dust load was inadequately defined and the CQs were not designed to prevent the buildup of dust. The intake screens were designed only for course particulates to reduce required fan pressure rise but could not prevent the fine dust particles from entering the CQ ducts. The mesh filters from Russian sleeping bags have been added to the intake inlet and exhaust inlet to reduce the amount of dust buildup, and to prevent some of these fine particles. Although the CQ were designed for disassembly and cleaning, it was very difficult to obtain crew time for maintenance. However, due to CQ ventilation redundancy, the crew was allowed to inhabit the CQ during troubleshooting activities and waiting for cleanings to be scheduled.

C. Mechanical System

The CQ structure serves to distribute launch and crew member loads, provide attachments to the vehicle, facilitate the mounting of components, and allow dissipation of thermal loads. No issues have been identified with the main structural components of the CQ. However, a minor issue was discovered during the maintenance cleanings performed for the airflow anomaly.

The crew identified a total of six fasteners as non-captive during three separate on-orbit cleaning operations to clean the starboard CQ intake and exhaust ducts. The crew photo documented the discrepant fasteners and marked them as non-captive. The fasteners were originally launched as captive fasteners installed in the starboard CQ. The captive features are either washers or retaining rings that allow the fastener to be removed from the substructure but remain attached to the panel so that it does not get lost. Since some of the fasteners were found to be non-captive, the crew had to show care when removing them and would temporarily store them.

Troubleshooting included checking with the vendors on the failures modes of the captive features as well as consulting with the installation technician to investigate possible failure modes. The root cause could not be directed at the type of fastener used since the captive feature was lost on different types of fasteners. The ISS Crew Quarters Strength and Fracture Assessment confirms that the areas of concern are capable of withstanding kick loads (where applicable) and launch loads, which are significantly higher than on-orbit loads with the possible exception being during maintenance.

Two general types of fasteners became non-captive. One was a Phillips® head captive machine screw and the other was a Live Lock™ stud. For the Phillips® head captive machine screw, the washer (captive feature) is installed by screwing it onto the fastener threads (Fig. 6). Just as it is easily screwed on, if the fastener is loosened out of the substructure but is continued to be loosened against the panel, it is possible to back out (unscrew) the washer during removal. If the crew is removing a panel and is unable to determine whether the fastener is completely removed from the substructure, the crew could continue to loosen the fastener while unfastening the captive washer. It is recommended to remove the Phillips® fasteners one turn at a time to avoid overloosening and backing out the captive washer during removal. For the Live Lock™ Studs (Fig. 7), failure modes include backward installation of the wire form ring (captive feature) on the fastener or the incorrect drill hole size of the retaining ring counterbore.

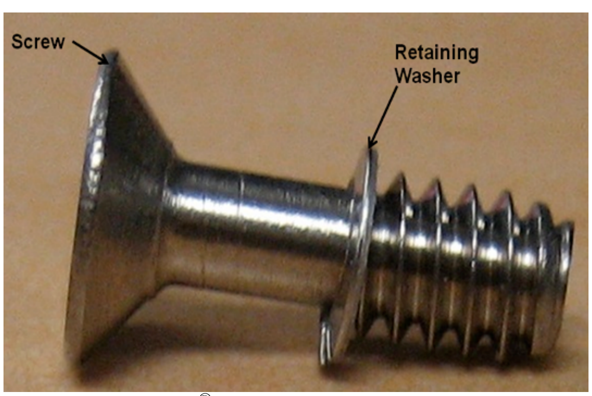

Figure 6. Phillips® head captive machine screw.

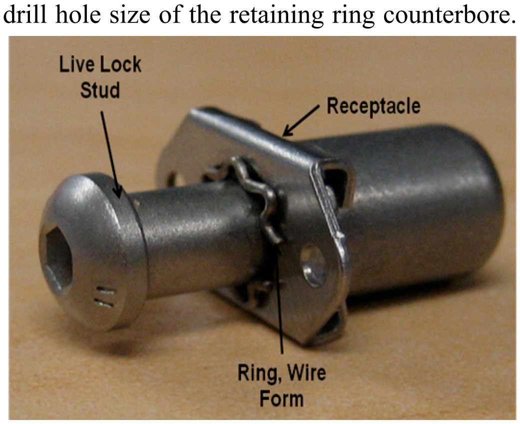

Figure 7. Live Lock™ stud.

Backward installation of the captive feature could cause misalignment and possible failure. The incorrect sizing of the counterbore could cause overstressing, thereby leading to failure. Build paperwork and drawings show that the correct instructions were given for the installation of these fasteners, but there is not enough detail on individual fastener inspection to determine whether one of the above issues occurred.

A fastener assessment was performed to determine whether the removal of current non-captive fasteners along with any other related fastener would compromise the structural integrity of the CQ when exposed to on-orbit loads.

The assessment analyzed all panels and hardware removed during routine CQ cleaning. If non-captive fasteners were discovered on subsequent cleanings of the CQ, the assessment determined which fasteners must remain and which could be removed should the non-captive nature of the fasteners become a hindrance to the cleanings. However, the current philosophy is that non-captive fasteners should not be removed permanently from the CQ.

The overhead CQ has been cleaned twice and the deck CQ cleaned once without a report of any non-captive or missing fasteners. The port CQ was cleaned in February 2012 and it was reported that there were three missing fasteners. It was determined that the port CQ had been cleaned prior to an approved procedure that identified the proper tools to use. It is possible that there was an unscheduled cleaning performed on the starboard CQ that could have led to the fasteners becoming non-captive.

All four of the CQ cleaning procedures have been updated to instruct the crew to loosen the Phillips® head captive machine screws one turn at a time to prevent the washers (captive features) from backing out during removal. The procedure also instructs the crew that the fasteners are susceptible to becoming non-captive and, therefore, the crew should show care when un-installing to prevent fasteners from getting lost. Spares are available on the ground to replace the captive features for all four types of fasteners, but it is not recommended that they be replaced at this time.

D. Acoustic Blankets

The interior and exterior walls of the CQ are covered with acoustic blankets to provide additional sound isolation for the crew. The blankets came in sections so that the pieces could be removed for cleaning or replacement. The exposed layer of the blankets is made of Gore-Tex® fabric because of its exceptional stain-resistance quality. Each CQ was deployed with a set of 16 acoustic blankets, three exterior blankets, and 13 interior blankets. No spare blankets were planned for development when the CQs were delivered; however, it was planned to replace them approximately every 3-1/2 years. The changeout was based on the CQ deployment date and the 10-year operational lifetime of the hardware. This would amount to two replacements during the life of a CQ. Based on CQ material stain testing and on-orbit data, rationale was developed to extend the replacement time of blankets.

Figure 8. Cover installed on CQ exterior doors.

In early 2011, a blanket replacement plan was recommended by the CQ project and approved by the ISS Program. A crew contact assessment was performed to investigate the possible contact on each blanket. This led to the identification of "low contact" and "high contact" areas. High contact areas were defined as locations where crew contact was seen daily (for example, doors, laptop area). Low contact areas were defined as locations where crew contact was minimal. The replacement plan recommended replacing low frequency crew contact blankets approximately every 5 years and covering high frequency crew contact blankets with covers (Fig. 8) approximately every 3-1/2 years. The covers would be attached on top of the existing blankets to protect the blankets from spills and wear. The covers do not contain any acoustic mitigation material. They consist of one layer of Nomex® and one layer of Gore-Tex®, identical to the outer layers of the acoustic blankets. In addition, the covers use and provide the same crew attachment points, such as grommets and Velcro®, as the current blankets. By developing lighter-weight covers instead of replacing the high frequency crew contact blankets, 16 kg and 0.16 m^3 of upmass and volume could be saved for the four CQs. One set of spare blankets and two sets of covers were manufactured in 2011 and early 2012. In July 2012, H-II Transfer Vehicle 3 delivered the first set of blanket covers to the ISS. The remaining covers are currently in stowage until required on-orbit.

E. Radiation Assessment

The TeSS was a protoflight unit developed in 2001 and launched on STS-105/7A.1. TeSS was located in the US Laboratory Module (LAB), Destiny, and provided a short-term solution for sleeping quarters that allowed the ISS

Figure 9. TeSS radiation shield (assembled).

crew member size to increase from two to three. TeSS provided a private sleeping volume with limited functionality as compared to the current ISS CQ in Node 2.[2] The operational life for TeSS was extended beyond the original 2 years, and TeSS was operational until 2010. In March 2010, TeSS was scheduled to be de-manifested from the ISS. At that time, the CQ project decided to assess the benefits and feasibility of integrating the TeSS radiation bricks into the CQ on the ISS for additional radiation protection. The radiation reduction benefit was characterized by the Space Radiation Analysis Group (SRAG) at Johnson Space Center (JSC) and the CQ project studied the integration feasibility of deploying and stowing the radiation bricks inside the CQ volume.

The TeSS radiation shield (Fig. 9) is assembled from eight custom brick assemblies and 20 flat brick assemblies (Fig. 10). Each brick assembly is composed of 5.08 cm of High-Density Polyethylene. Two 2.54-cm blocks are pinned together to make the 5.08-cm brick. Each block is wrapped in a Nomex® sleeve and then assembled into the 5.08-cm brick that is then wrapped in aluminum tape.

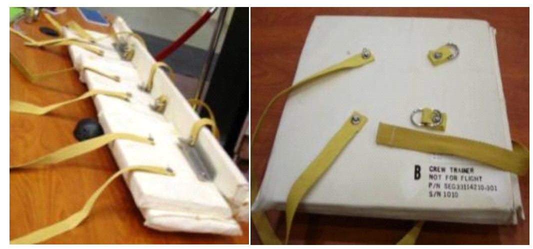

Figure 10. TeSS brick assemblies – custom and flat bricks.

The goal of the radiation analysis completed by SRAG was to provide input on the most effective placement of the TeSS radiation bricks in the CQ to reduce crew exposure during a contingency radiation event. Repurposing the TeSS radiation bricks provides a benefit to crew health by supplementing the already existing radiation protection in the four ISS CQs located in Node 2[2] and adheres to the As Low As Reasonably Achievable principle, which guides NASA Radiation Protection.

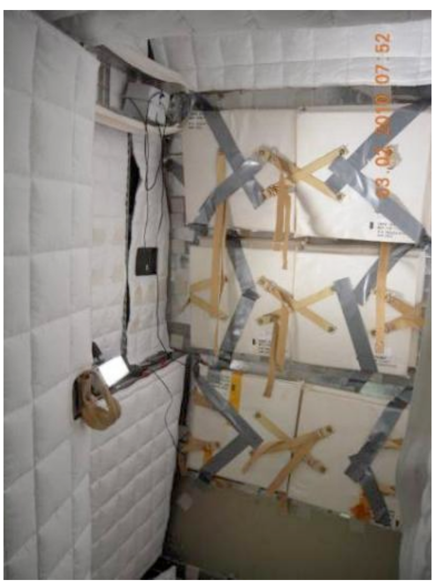

Figure 11. Six TeSS bricks installed on CQ back wall.

The analysis evaluated eight different configurations of multiple flat TeSS bricks in the CQ volume assuming that all four CQ are located in Node 2. The reduction of effective dose results are based on ISS Increment 21 environment for the low Earth orbit estimates, and the 1972 King Spectrum for worst case solar particle event estimates. The analysis concluded that addition of the TeSS radiation bricks to the upper body locations in CQ is the best use of the material and there is a clear benefit to integrating the additional radiation protection inside the CQ. Deploying six TeSS bricks on the back wall of each of the CQs can achieve approximately 16% of additional radiation reduction in nominal conditions. Furthermore, if the bricks are placed in other configurations that were analyzed, additional radiation reduction in nominal conditions can range from approximately 4% to 16%.

The integration assessment evaluated five different configurations of six flat brick assemblies inside the CQ volume. The CQ trainer that is located at JSC was used for the evaluation. The five different configurations included permutations of attaching the bricks to the CQ back wall (Fig. 11), back wall and floor, and sleep wall and floor. Additionally, the evaluation considered whether the radiation bricks could be deployed on the CQ back wall underneath the CQ blankets. Installing the bricks in this manner would keep the integrity of the crew attachment points (Velcro®) for personal items on the back wall, as well as eliminate the abrasion points from the TeSS brick pins.

In addition, the SRAG further characterized the five different configurations in terms of additional days in orbit for a crew member, where low is approximately 3 additional days, medium is approximately 6 additional days and high is approximately 12 additional days (reference Table 1). As confirmed by the radiation analysis, the configuration with six bricks located on the CQ back wall provided the most effective reduction. Table 1 shows the results for each configuration evaluated in terms of additional days in orbit and number of crew attachment points lost based on placement of the TeSS bricks in the CQ on top of the acoustic blankets. There are approximately 90 crew attachment points on the CQ back wall that could be affected by TeSS brick placement.

Table 1. Results for TeSS Bricks Installed in CQ

Configuration	Additional Radiation Protection (high, med, low)	# of Velcro points lost
6 bricks on back wall	high	73
2 on lower back wall, 2 on lower sleep wall, 2 on floor	low/medium	24
2 on lower back wall, 2 on kick panel, 2 on floor	low	40
2 on floor, 3 vertically on back wall, 1 on sleep wall	med/high	24
4 on sleep wall, 2 on floor	medium	0

Based on the integration evaluation, the CQ project team concluded that the crew has many options for deployment and/or stowage of the radiation bricks in the CQ volume. The CQ project considers the bricks as crew preference items and all configurations of the bricks are acceptable. Currently the 20 flat brick assemblies are on-orbit as crew preference items and are used in the CQs at the discretion of the crew.

IV. Conclusion

A quiet, private retreat for each crew member is essential to long-term mission success. CQs have been providing that function successfully since 2008. In addition to a private retreat, CQs contain radiation protection, individual ventilation systems, and personal communications systems. Crew feedback indicates that the crew is generally happy with the performance and capabilities of the CQs. The few on-orbit issues that occurred are understood and preventative actions are in place. Even through the troubleshooting of these issues, the CQs provided uninterrupted living arrangements due to the redundancy built into the system.

Acknowledgments

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