International Space Station Crew Quarters Ventilation and Acoustic Design Implementation

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The International Space Station (ISS) United States Operational Segment has four permanent rack-sized ISS Crew Quarters (CQs) with each providing a private crew member space. The CQs use Node 2 cabin air for ventilation and thermal cooling, as opposed to conditioned ducted air from the ISS Common Cabin Air Assembly (CCAA) or the ISS fluid cooling loop. Consequently, CQ can only increase its interior airflow rate to reduce the temperature difference between the cabin and the CQ interior. However, increasing airflow causes an increase in acoustic noise, so streamlined airflow distribution is an important design parameter. The CQ utilizes a two-fan push-pull configuration to ensure fresh air at the crew member's head position and reduce acoustic exposure. The CQ ventilation ducts are conduits to the louder Node 2 cabin aisleway, which required significant acoustic mitigation controls. The CQ interior needs to be below noise criterion curve 40 (NC-40). The design implementation of the CQ ventilation system and acoustic mitigation are very inter-related and require consideration of crew comfort balanced with use of interior habitable volume, accommodation of fan failures, and possible crew uses that impact ventilation and acoustic performance. Each CQ requires approximately 15% of its total volume and approximately 5% of its total mass to reduce acoustic noise. This paper illustrates the types of model analyses, assumptions, vehicle interactions, and compromises required for CQ ventilation and acoustics. On-orbit ventilation system performance and initial crew feedback are also presented. This approach is applicable to any private, enclosed space that the crew will occupy.

Nomenclature

BISCO®	=	barium-impregnated silicon oxide
CCAA	=	Common Cabin Air Assembly
CO_2	=	carbon dioxide
CQ	=	Crew Quarter
dB	=	decibel
dBA	=	decibel A-weighted
ISS	=	International Space Station
JPM	=	Japanese Pressurized Module

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JSC	=	Johnson Space Center
NC	=	Noise criterion
TeSS	=	Temporary Sleep Station
ULF	=	Utilization Logistics Flight

I. Introduction

After the launch of Space Shuttle assembly flight STS-131 (19A) in April 2010, the International Space Station (ISS) will contain the full complement of four Crew Quarters (CQs). The CQs are located in the four rack locations of Node 2, Bay 5 and form a ring. Overviews of the general architectural layout of the CQ and the general tradeoffs during its development have been described in previous papers.[1,2] However, a brief overview of the layout is necessary before providing a more detailed discussion of the acoustical challenges addressed by the CQ design.

Functionally, CQ provides an acoustically quiet and visually isolated volume in which crew members can sleep, relax, and retreat to a private space. The ISS volume allocated to CQ is a standard ISS rack volume with two protrusions, as shown in Fig. 1. Approximately 8 cm of additional head room is provided with a deployable ceiling called a pop-up. The pop-up, which is integral to the CQ rack, is deployed after the CQ rack is installed. In the on-orbit deployed configuration, a 30-cm protrusion called the bump-out extends into the Node 2 aisleway. This bump-out volume provides no direct habitable volume for the crew, with the exception of the door passage. The bump-out volume was allocated to the ventilation system.

The total deployed volume of the CQ is approximately 2.1 m^3. It was desirable to provide as large a habitable volume for the crew member as possible. This habitable volume goal presented a design challenge to provide adequate airflow, minimize fan generated noise, and reduce exterior noise transmitted into the CQ interior.

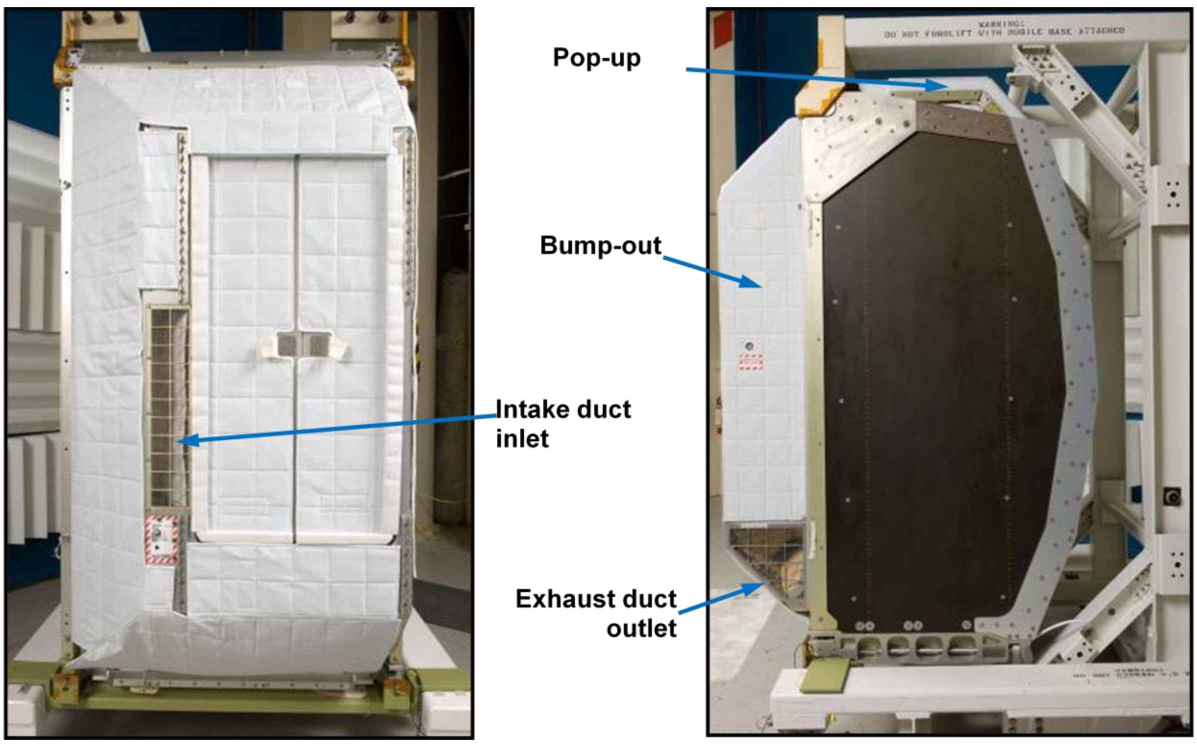

Figure 1. External view of front side toward aisleway (left) and aft side (right) of Deck CQ on-orbit configuration in a rack handling adapter (white structure).

II. Ventilation/Acoustic Architecture

The physical and operational considerations of the CQ ventilation and acoustics architecture were determined at several levels. Operationally, at the vehicle level, the Node 2 Common Cabin Air Assembly (CCAA) can be adjusted to reduce the ISS aisleway temperature to approximately 18°C. Since the aisleway air temperature can be controlled, the CQ was not provided interfaces to the ISS coolant loops. This required the CQs to use air exchange with the aisleway to provide crew comfort. Each CQ draws in aisleway air perpendicular to the rack face through an intake duct inlet; shown in Fig. 1. The air is circulated through the CQ volume by two fans. Inside the CQ, the air absorbs the crew member's metabolic heat (100-132 W) and the electronics' waste heat (approximately153 W). The air is then directed though the CQ exhaust duct outlet and directed parallel to the rack face and down the aisleway toward the Node 2 CCAA air return. These CQ air intake and exhaust directions are consistent with the general Node 2 air circulation, which allows the CCAA smoke detector to identify combustion events within the CQ. These intake and exhaust directions also minimize recirculation of air between the CQs which would result in some CQ interiors not receiving adequate cooling. The primary vehicle-level interface ventilation requirements for the CQ are as follows:

- 0.42-5.1 m^3/min of airflow
- < 76 m/min exhaust air velocity

All the CQs are physically located in one area: Node 2, Bay 5. Node 2 is at one end of ISS, so there is less crew translation that can impart impulse noise and vibration to the CQ interior. Node 2 also provides a lower acoustic environment because the remaining four rack bays are relatively quiet electric power converter racks. The primary vehicle-level interface acoustic requirements for the CQ are:

- CQ interior between noise criterion (NC) curves 25 and 40
- External noise environment in Node 2 aisleway of NC curve 52
- CQ exterior acoustic emissions of NC curve 40

It was acknowledged at the beginning of the CQ project that ventilation and acoustics were the primary functional requirements and would be the most challenging to satisfy. If the CQ ventilation did not provide sufficient temperature control (flow rate and direction) for crew comfort, crew members might not use it and use the ISS aisleway instead. Similarly if the CQ interior was not sufficiently quiet, the crew would need hearing protection or sleep medications—both of which are unacceptable for long-term use. The ventilation system also removes carbon dioxide (CO_2), which is an asphyxiation hazard. The asphyxiation hazard is categorized as a catastrophic hazard that requires fan redundancy.

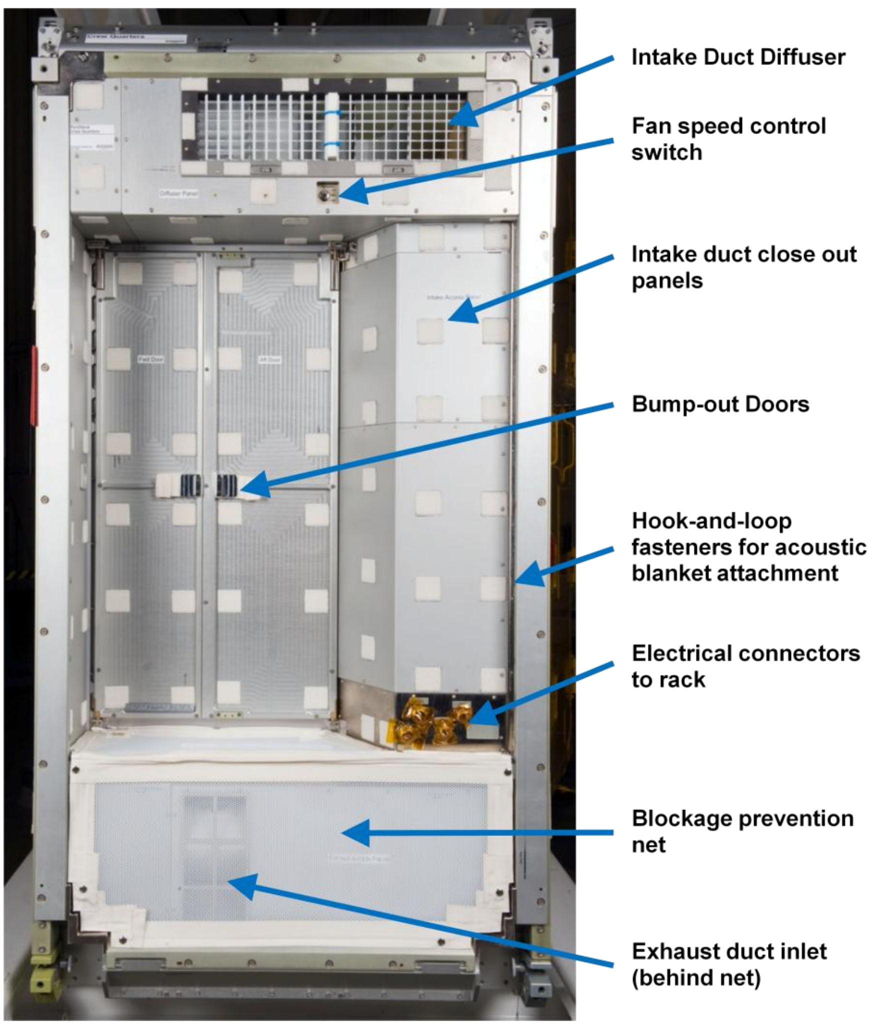

Figure 2. Deck CQ in the launch configuration.

The CQ project addressed these vehicle interface requirements by decomposing them into the following three primary hardware systems: fans, ducts, and structure/blankets. These three areas are interrelated and were developed in parallel to meet hardware delivery schedule constraints. Figure 2 illustrates the location of all bump-out features that are accessible to the crew member when inside the CQ without the acoustic blankets. The acoustic blankets, which are not shown, attach to the structure with hook-and-loop fastener patches. In Fig. 2 the CQ is pictured in the launch configuration where the bump-out is reversed and mounted to rack front so there is no aisleway protrusion.

Figure 3 illustrates the interior of the CQ bump-out in the on-orbit deployed position. In this configuration, the white interior acoustic blankets cover most surfaces to reduce acoustic noise transmitted from the ISS aisleway. In the deployed configuration, it is difficult to obtain a single, full-height view of the bump-out. The general layout and airflow of the intake duct layout and exhaust duct layout and airflow are depicted in Figs. 4 and 5, respectively. The red line represents the airflow path. These shapes and features will be described in greater detail in the following sections.

Figure 3. Port/Deck CQ interior in the on-orbit deployed configuration.

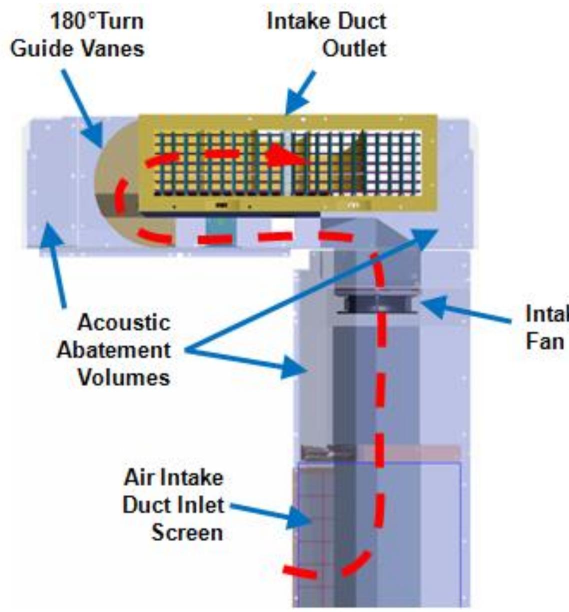

Figure 4. Intake duct ventilation flow path and volume dedicated to abatements.

A. Fan Architecture

Two fans per CQ were required to prevent a single-point failure (complex implementations of redundant motor windings and internal sensors were not considered due to schedule constraints). Both serial and parallel implementations of the dual-fan system were investigated as possible solutions. Several characteristics were compared; including: power efficiency, pressure head capability, packaging, acoustic interactions, and failure modes. A standard 90-mm fan was the largest common-sized fan that could be packaged in each duct.

The serial fan configuration has one fan downstream of the first fan. These fans can be physically mounted in separate ducts but connected by the CQ interior volume. This configuration allows each fan to add its head pressure capability to move a single column of air through the ducting, thus allowing the system to operate at a higher pressure head for a given flow rate. The fan pressure head is required to overcome the backpressure (pressure loss) that is generated by the ventilation ducts' length and number of bends.

The parallel fan configuration has two fans side by side or in parallel ducts. The fans can be physically separated into separate parallel ducts of equal back pressure. This configuration allows each fan a higher flow rate for a given pressure head. Figure 6 compares a single CQ fan, two CQ fans in series, and two CQ fans in parallel.

As will be discussed in the "duct acoustic considerations" section later, the ducting required numerous bends and abatements to reduce acoustic noise from the ISS aisleway and the CQ fans themselves. The ducts' backpressure is represented in Fig. 6 as a black "system resistance" curve. In the serial configuration, one fan can be near the crew member's head and the other near crew member's feet. This configuration requires less duct volume near the crew member's head and increases the perceived interior volume of the CQ. In the parallel configuration, both fans (or at least the duct outlets) must be near the crew member's head. This orientation is required to provide the coolest air to the crew's head and ensures CO_2 removal when the CQ's door is open. This set-up requires increased duct volume

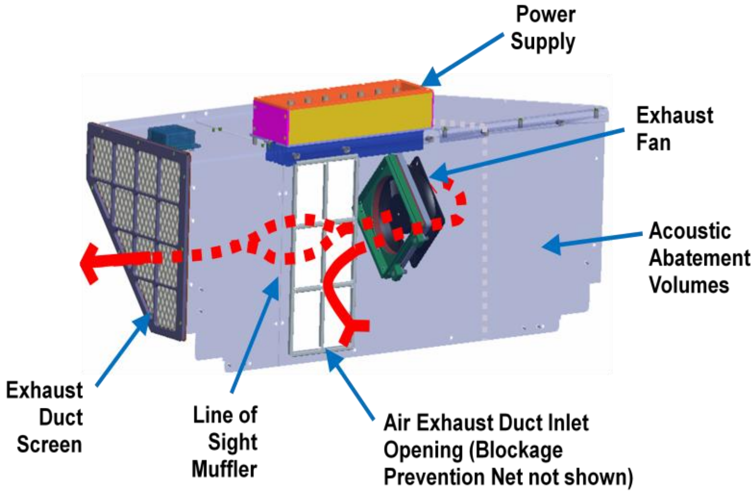

Figure 5. Exhaust duct ventilation flow path and volume dedicated to abatements.

near the crew member's head and decreases the perceived interior volume of the CQ. The parallel fan configuration also requires the presence of an isolation damper to prevent back flow out the duct if one fan fails.

The point of intersection between the system curve and either the serial fan curve or the parallel fan curves of Fig. 6 illustrates the differences in flow. The serial fan configuration can provide 2.7 m^3/min of airflow and is in an area of stable fan performance; by contrast, the parallel fan configuration provides 2.1 m^3/min, and is in an area of potentially unstable fan performance. This unstable region of the parallel fan curve could result in acoustical oscillations from fan/duct backpressure interactions.

Based on the reduced duct volume at the crew member's head and the increased airflow rate at higher duct backpressures, the serial fan configuration was selected. The calculated flow and backpressure requirements combined with acoustical considerations enabled the number of commercially available fans to be narrowed. The Johnson Space Center (JSC) Acoustics Office assisted in developing an acoustics noise control plan and evaluation of candidate fans. The following general guidelines were used narrowing fan selection:

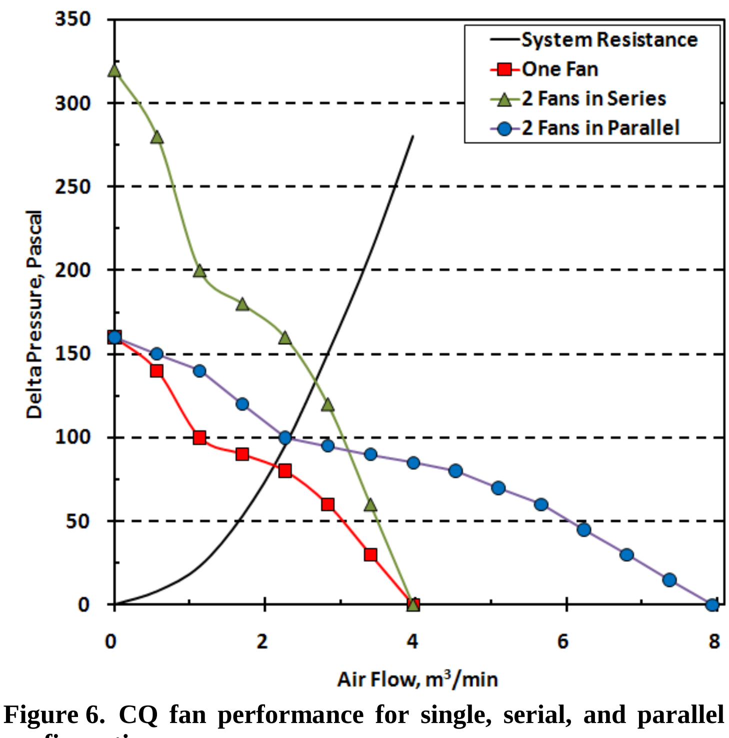

Figure 6. CQ fan performance for single, serial, and parallel configurations.

- Fans with more fan blades are generally quieter because the blade loading decreases.
- Generally, fans with plastic blades are quieter than fan with metal blades.
- Lower fan rotational speeds are generally quieter.
- Fans should be located away from surface panels. This helps to avoid turbulent airflow, which causes greater noise.
- Design ducting to muffle and absorb noise.
- Keep flow paths smooth.

Commercial fans were reviewed, but normally only fans used in previous military or aerospace applications had acceptable motor and drive electronics. The largest fan frame size, 90 mm that could be reasonable packaged in the CQ duct volume was selected to allow it to operate at lower speeds. However, most fans in this size range were optimized for higher flow and back pressure, required more electrical power, and generated more acoustic noise than was acceptable to the CQ project. The JSC Acoustics Office recommended five fans for testing. Each fan was mounted in a simple test (Fig. 7) stand that allowed for varying the backpressure to determine the actual flow rate, power draw, and acoustic signature. Most fan manufacturer acoustic data represent fans operating in free air without backpressure. As a fan is subjected to backpressure, the acoustic noise can increase significantly. Testing resulted in selection of an EBM-Papst, Inc (Farmington, Conn.) 4184N/2XH fan as the best

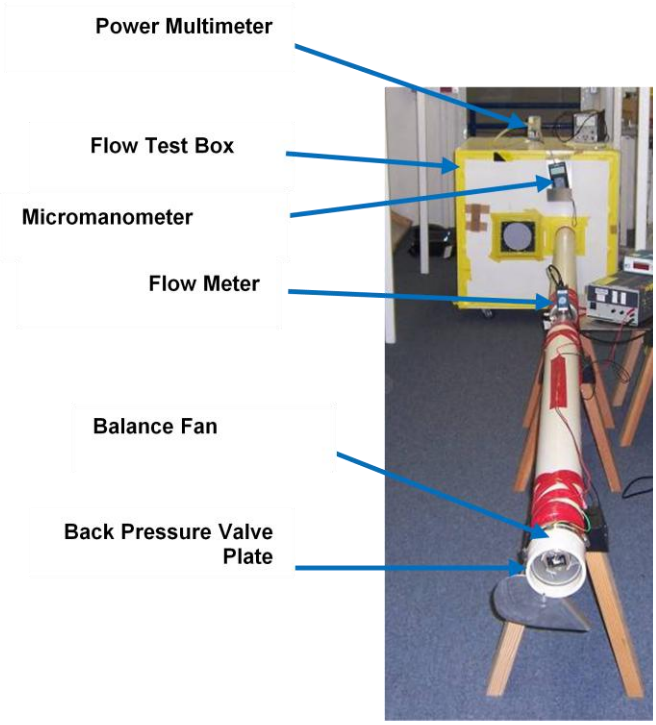

Figure 7. CQ fan flow performance test stand.

compromise between power, flow rate, pressure, size and acoustics. The fan also contained a tachometer to monitor rotational speed, which was used as part of CQ fault detection.

1. Fan Operation versus Thermal Loads

Since a CQ is cooled by air exchange with the ISS aisleway, increasing the airflow rate by increasing the fan speed decreases the temperate increase (delta) with respect to the aisleway. For flows above approximately 2.4 m^3/min, there is little additional cooling, Fig. 8. As airflow increases, fan-generated noise and duct broadband noise increase. This resulted in the CQ maximum fan speed setting to be limited to 2.6 m^3/min. The fan speed control was set at three speeds: low (1.8 m^3/min), medium (2.3m^3/min), and high (2.6m^3/min). Continuous speed control while feasible, introduces less reliable and more complex electrical components with the air speeds not changing perceptively (1.8 to 5.5 km/h). Details of the thermal loads were described in a previous paper[1] but the resultant temperature rise from the electrical and human heat loads is repeated in Fig. 8.

B. Duct Architecture

The system curve (Fig. 6) increases rapidly due to the number of bends in the limited CQ bump-out volume, which limited the effective duct diameter. Although the duct shape changes several times to fit in the volume around the doorway, the duct cross-sectional area is maintained at approximately 120 cm^2. The serial fan configuration allowed one duct at the crew member's head position, named the "intake duct", to transfer air from the ISS aisleway to the CQ's interior. The duct at the crew member's foot position, named the "exhaust duct" transfers air from the CQ's interior to the ISS aisleway. When the CQ door is open each fan/duct system works independently because air can short-circuit through the door. Another benefit to the serial fan/duct configuration is that it allows the CQ power supply to be mounted downstream of the CQ interior environment so that the electronics stay cool while rejecting about 17 W into air after the air exits the CQ habitable volume. This resulted in a decrease in interior air temperature of approximately 0.6^{o}C or the equivalent of 0.4 to 0.7 m^3/min of airflow due to the relatively flat curves of Fig. 8.

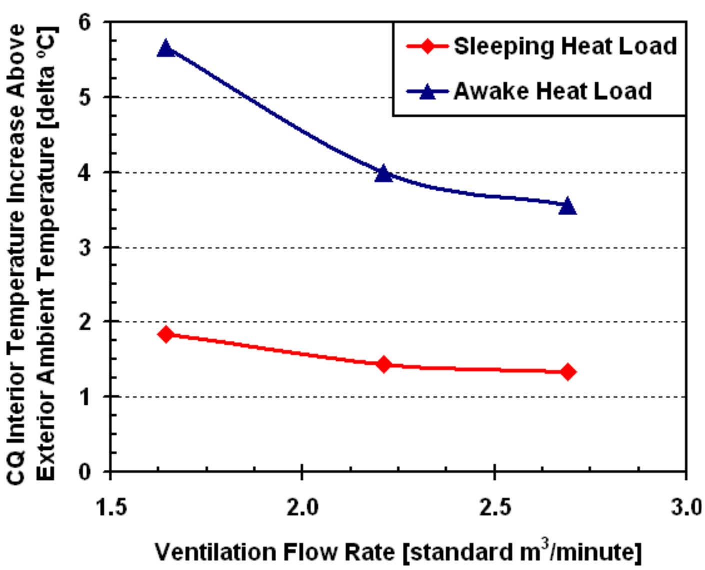

Figure 8. Temperature rise verses flow rate.[2]

The CQ ducts not only direct air but also must absorb fan-generated noise and reduce the noise transmitted from the exterior. Conventional rigid ducting would direct the NC-52 aisleway noise into the CQ interior and easily exceed the NC-40 requirement. The ventilation system could not protrude into the CQ rack volume because of system-level trade studies, which indicated the best manifest/crew deployment configuration for the bump-out was to be removed and reversed to fit completely flush with the rack volume as a single unit for launch. This also provided structural rigidity during launch and reduced crew time during assembly. The total bump-out volume is about 0.39 m^3. The door size of the previous Temporary Sleep Station (TeSS)[1] was maintained and this translation area was maintained through the bump-out depth. The door volume used approximately 50% (0.19 m^3) of the bump-out volume and provided additional interior crew member volume in the elbow/torso area—which is useful when using the laptop table or changing clothes. This configuration allowed the maximum interior habitable volume. Greater duct volume was allocated to the inlet duct (approximately 34% of the bump-out volume (0.13 m^3), because the outlet is at the crew head position. The volume shape was complex, running along the forward edge of the door and between the top of the door and the upper bump-out chamfer. The exhaust duct volume, (approximately 11% of the bump-out volume (0.04 m^3)), was located below the door and the lower bump-out chamfer. The remaining bump-out volume was used for structure and miscellaneous hardware.

1. Duct Acoustic Abatement Considerations

The interior surfaces of the duct needed to be covered with sound-absorbing material that was acoustically porous, capable of absorbing a wide range of acoustic frequencies, low frangible (particle generation), capable of being cleaned, and replaceable, and be able to meet ISS flammability and mold/fungus resistance standards. Extensive configurations of foams, fills, coverings, and stiffening materials were tested with the assistance of the JSC Acoustic Office. The final flight abatement design consisted of 19 foam blocks and fabric blankets for the CQ duct surfaces. The integrated abatement shapes provided a smooth flow surface and used all the remaining bump-out volume. The inlet flow path directs air around three 90-deg turns and one 180-deg turn. The intake fan was located close to the front of the duct to allow more opportunities for absorption. The exhaust flow path provided one 90-deg turn, one 180-deg turn and one muffler region. The depth of the foam at each turn was varied to assist in the absorption of particular wavelengths of acoustic noise. Several functional duct mocks were used to develop the abatement implementation.

2. Duct Mockup Acoustic Tests

In addition to the mockups used for crew member evaluations[1], the project created a series of full-scale ducts early in the development phase. These full-scale units were required to characterize the competing requirements of power draw, heat rejection for crew comfort/electrical cooling, sound pressure level requirements, packaging limitations, and manufacturability concerns. The first unit had a wood structure and melamine foam abatements to line the flow path and attenuate the sound pressure levels. The benefit of the wooden mock-up was the ability to easily reconfigure it with multiple abatement materials. This enabled abatements to be tailored to the acoustic frequencies of the fan and external environment. The initial duct test stands were comprised of separate intake and exhaust duct structures to evaluate individual duct performance; see Figs. 9 and 10.

The wooden test unit was used to measure CQ-specific initial design data for: fan placement within the ducts, system backpressure, flow rate assessments, and rough acoustic measurements. The initial fan and flow testing allowed determination of fan rotational speeds, initial placements of flow sensors, and backpressure of abatement

Figure 9. Initial functional intake duct acoustic testing.

Figure 10. Initial functional exhaust duct mockup.

lined ducts. The second round of testing with the wooden test articles was conducted to improve acoustic sensitivity fidelity of fan placement in the duct. In Fig. 9, the horizontal aluminum plate between the yellow melamine abatements held the intake fan. The intake fan position was adjusted vertically to characterize its effect on acoustic levels. Similar testing was done to the exhaust duct fan placement. The third round of testing investigated placement of airflow sensors and flow distribution at the duct outlets. The airflow sensors function is similar to that of a hotwire anemometer. The sensor heats an area of its surface, and the airflow across the sensor cools that area down. The sensor compares the ambient and current temperature of the heated area and evaluates them against the heated area's theoretical temperature without airflow. The sensor provides a voltage output proportional to the change in airflow across the heated area. With the many turns in the ducting, it was difficult to find a location that provided a consistent representative air speed for flow monitoring. Eventually, the intake duct geometry was slightly altered to place the flow sensor in a narrower cross-sectional area that provided more uniform airspeed changes with changing flow rate. Similarly the exhaust flow sensor was moved to the divergent zone's highest air speed location. Moving both flow sensors to higher airspeed regions was required because testing revealed that ducting areas with low air speeds did not change sufficiently during fan/duct failure scenarios. During detailed airspeed measurements of the intake duct outlet, we discovered that the centrifugal effects of the duct bends was larger than expected; see Fig. 11 (zone E). The majority of the airflow was forced to one end of the intake duct outlet diffuser. A five-channel set of guide was added to more evenly divide the airflow across the diffuser. Figure 11 is the result of 138 anemometer readings at each intervane opening in the intake duct outlet diffuser (see Figs. 2 and. 4). Figure 11 illustrates a contour plot of the airspeed perpendicular to the diffuser that would blow into the CQ. The letters A through E represent the channels between the guide vanes. There are five regions of higher flow (>30 m/min) which correspond to the outer edge of each channel defined by the guide vanes. For example, the upper midpoint between the letters A and B is the edge of a guide vane. Without the guide vanes, most of the airflow would be through channels D and E.

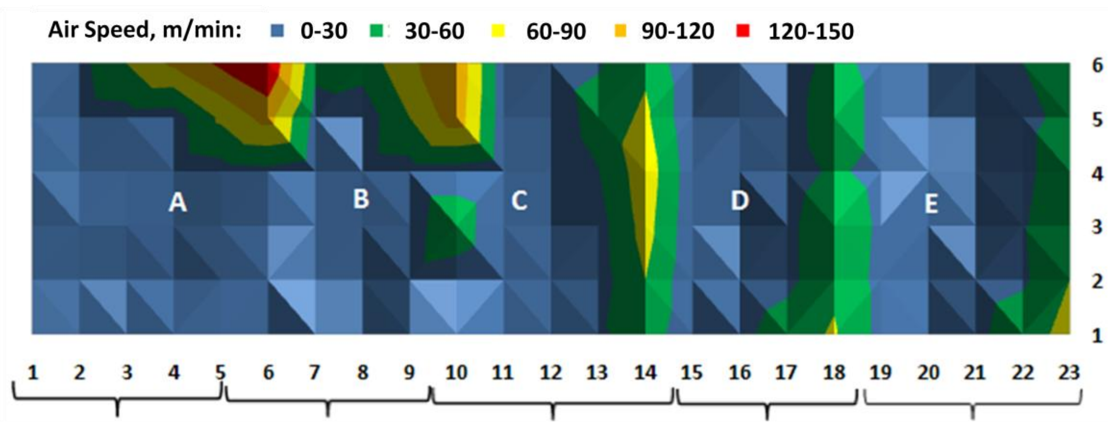

Figure 11. Airspeed at each opening in air diffuser outlet after addition of flow vanes to create five air channels (A through E).

3. Flight-like Duct Abatement Tests

As previously discussed,[1] a full-scale mid-fidelity mockup was used for crew member evaluations and very useful in defining the overall CQ layout. This mockup was fabricated from aluminum and composites similar to the flight unit. Flight-like acoustic blankets and duct abatements were also used to test the integrated acoustic mitigation's effectiveness. Several abatements required minor adjustments for proper fit. Testing revealed the intake duct fan's elastomeric mounts did not properly isolate the fan, resulting in structural noise transmission. The design solution was to capture the fan within one of the foam abatements; see Fig 12. This soft-capture approach reduced the structure-transmitted noise but could possibly damage the abatement during launch, so the fan was launched separately and installed on orbit. Additionally the mid-fidelity mockup revealed a slight acoustic interaction between the intake and exhaust fans. Inside the CQ interior, the slight difference in the intake and exhaust fan speeds resulted in a harmonic modulation or "beating" noise at the blade pass frequency of the fans. The design solution was to reduce the exhaust fan speed by aproximately10 RPM to prevent the acoustic interaction. Testing indicated that the fan blade pass frequency noise would still slightly exceed the acoustic requirements. Several minor abatement adjustments were incorporated into the final design to reduce the tonal noise associated with the fan blade pass frequency.

Figure 12. Intake fan soft captured in foam abatement.

C. Structurally Transmitted Acoustic Architecture

If the ISS ventilation equipment and payload-mounted fans/pumps meet their acoustic requirements, the need for mitigating structure transmitted noise would be greatly reduced. There is a significant need for the development of inherently quiet fans and pumps to reduce the mass dedicated to passive acoustical controls. The ISS aisleway noise (NC-52) is also transmitted through the CQ's structure. Candidate materials were tested for their acoustic transmission losses from 63 to 10,000 Hz. Larger transmission losses indicate greater absorbance of sound energy.

1. Structural Materials

The CQ racks were constructed of an aluminum frame that captured panels of composite (black material in Fig. 1) or plastic material. The aft side wall, forward side wall, lower back panel, and floor were constructed of light weight carbon fiber skin/Nomex® honeycomb core of 2.8 cm thickness. A single Nomex® honeycomb core, a double honeycomb core (two cells of half the total thickness with a parting sheeting between them), and the TeSS' Fibrelam® material were tested. The single and double cores' attenuation were essentially identical below 800 Hz. The double core provided 1 to 3 dB greater attenuation above 800 Hz. The Fibrelam® transmission was similar to the carbon fiber composites below 200 Hz but produced generally 5 to 20 dB less attenuation above 200 Hz compared to the carbon fiber/Nomex® composites. The single Nomex® core carbon fiber composite panels were selected because ease of manufacture outweighed the minor acoustical benefit. The lowest transmission loss was 12 dB at 100 Hz.

The CQ racks also incorporated 125 kg of ultra-high molecular weight polyethylene for reduction of radiation exposure. The 6-cm thick panels are located in the pop-up ceiling and back walls (except for the lowest panel). This material was selected for its radiation reduction properties. The lowest acoustic transmission loss was about 12 dB at 100 Hz.

The CQ rack bump-out is constructed primarily of aluminum (0.1 to 0.7 cm thickness) due to the many angles and internal attachment points. Aluminum exhibits little transmission loss below 300 Hz. At 300 Hz, the aluminum transmission loss is about 7dB. Since the transmission losses below 300 Hz were so low, the exterior acoustic blankets covering the bump-out incorporated acoustic barrier materials.

2. Acoustic Blankets

As summarized in the preceding paragraph, the CQ bump-out does not provide much low-frequency acoustic mitigation, so a blanket is required. The acoustic blanket design had to balance flammability, cleanability, and acoustic requirements. Nomex® is often used in space applications because of its flammability resistance, but it can retain stains, trap dirt, and be difficult to clean. Five fabrics (Nomex®, Ortho fabric, a Teflon® fabric, and two Gore-Tex® fabrics) were evaluated for stain-resistance and cleanability. Soiling was evaluated by combining elements from ASTM D4265, *Standard Guide for Evaluating Stain Removal Performance in Home Laundering*, AATCC Test Method 118-1983, *Oil Repellency: Hydrocarbon Resistance Test*, and the AATCC Evaluating Procedure – *Gray Scale for Staining*.

- The fabric samples were soiled with instant coffee (a beverage available on the ISS) and an oil that simulates human skin oils.
- The Gore-Tex® and Teflon® fabrics were substantially more resistant to staining than the Nomex® and Ortho fabrics.

The air permeability of the fabrics was also evaluated using ASTM D737, *Standard Test Method for Air Permeability of Textile Fabric*. Fabrics with higher air permeability allow more sound energy to transfer through to lower layers of sound absorbing material.

- The Nomex® (as used on TeSS) had the lowest air permeability of 2.0 m^3/h whereas the other materials ranged from 17 to 140 m^3/h depending on material weave.
- Evaluation of the two tests resulted in the selection of a white Gore-Tex® fabric for the interior surface of the blankets. White Nomex® was selected for the external surface next to the CQ structure for its flammability resistance and relatively high stiffness to give the blankets "body" during handling and installation.

The primary sound blocker is a barium impregnated silicon oxide (BISCO®) elastomeric sheet, with a surface density of 1.2 kg/m^2. BISCO® provides a minimum of 11 dB reduction. A range of sound-absorbing interior materials was tested including: Nomex®, Durette® felt (used on TeSS), Kevlar®, and Thinsulate™.

- Initially Thinsulate™ was chosen because it was 26% lighter per unit area than Kevlar®.
- However, Thinsulate™ unexpectedly failed the flame-propagation test, it was replaced with Kevlar® because Kevlar® is lighter per unit area than Durette® felt.

The CQ interior blankets are similarly constructed except without the BISCO® because the CQ structure provides adequate acoustic blocking. The blankets' final construction is depicted in Fig. 13. The blankets were quilted to prevent billowing. The blankets include 5x5-cm hook-and-loop fasteners patches used on the backside to attach the blankets to the CQ structure, and similar patches are used on the front to allow attachment of crew member items. Grommets reinforce mounting holes for D-rings that are used to hold crew member items with elastic cords or ties. The amount of through stitching used for quilting and attachment hook-and-loop fasteners is minimized because the stitching compresses the thickness thereby reducing acoustic absorption. Quilting was limited to every 10 cm and the hook-and-loop fasteners were bonded to the fabric and corner-stitched through the top fabric surfaces to minimize blanket compression, Fig 14.

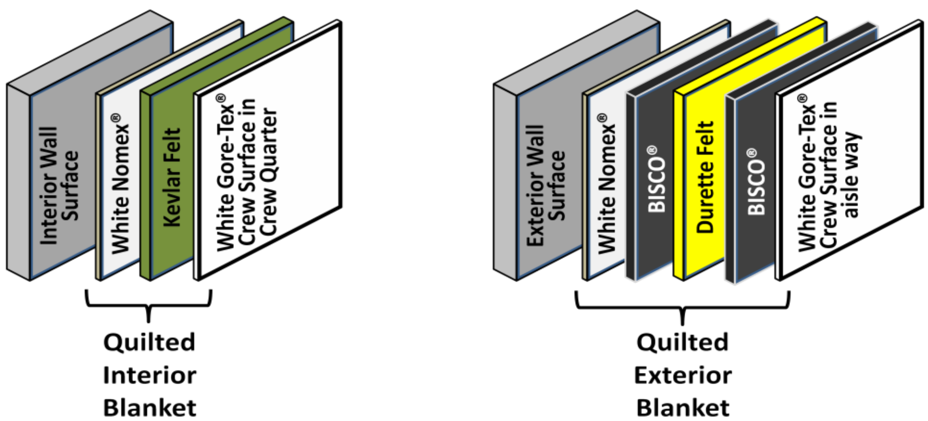

Figure 13. Interior (left) and exterior (right) acoustic blanket material layers.

III. Flight hardware implementation

The CQ design completion was later than planned and resulted in limited opportunity for full flight tests of the integrated fans, abatements, and blankets. Program funding limits had also removed the qualification CQ unit. This removal resulted in use of the mid-fidelity mockup being extended beyond the original planned crew member evaluations. The mid-fidelity mockup was also used to test portions of the blankets, fan operation, and duct abatements.

A. Acoustic Blankets

The three-dimensional external bump-out acoustic blanket was fit-checked with the bump-out during its mechanical assembly. The interior blankets were also fit tested to the rack structure during assembly, which revealed that several hook-and-loop fastener patches were not in proper alignment due to inadvertent mirror image differences between the port and starboard configurations. These enabled minor adjustments to blanket patterns as all four CQs were being fabricated simultaneously. Despite acoustic testing to select lighter-weight materials, the acoustic blankets still weighed about 18 kg per CQ and occupied about 0.1 m^3 of volume.

Figure 14. Typical CQ interior sleep wall acoustic blanket.

B. Duct/Abatements Integration

Figure 15 shows the CQ bump-out during final assembly without interior acoustic blankets, close out panels, and antiblockage net. This configuration allows the majority of ventilation abatements to be visible. The gold surfaces are Durette® felt and have good air permeability characteristics. The abatement interior composition varies depending on the abatement piece, but typically contains an open cell polyimide foam external contoured shape and a Thinsulate™ batting interior. The olive-drab green exterior is a Nomex® covering used to reduce the frangibility. The abatements are held to the aluminum walls with a combination of hook-and-loop fasteners and light compression. All of the abatements are designed to be cleaned with the ISS vacuum cleaner outfitted with an upholstery brush attachment. The abatements can also be replaced if they are damaged or become unacceptably dirty.

C. Certification Acoustic Testing

Before final delivery, CQ rack acoustic certification testing was conducted to compare the acoustic emissions with CQ and ISS acoustic requirements. Note that the CQ acoustic requirements include the maximum allowed exterior rack emissions, and the interior envelope sound pressure levels (minimum and maximum).

The ISS acoustic requirements for hardware and interior volumes were developed from experience gained during the Space Shuttle Program and the NASA missions to the Russian *Mir* space station. The requirements are written in terms of NC curves, which allow higher sound pressure levels in the low-frequency octave bands at which human hearing is less sensitive. The definition of the NC rating system for noise fields and its correlation to subjective impressions of noise are detailed by the Beranek text[3]. NASA-STD-3000[4] habitability standards establish NC-50 as the acoustic work environment and NC-40 as the limit for sleep environments, and provides the rational for their selection. The NC-50 curve is the limit at which 75% of conversation can be understood with a normal speaking level at 1.5 to1.8 m. The NC-40 limit for sleep environments was established as the level needed to provide auditory rest for the crew member to prevent stress and anxiety and to promote physical relaxation. Additionally the minimum requirement for the sleep environment is the sound pressure level must exceed NC-25. This minimum requirement was established due to feedback from crew members indicating that they wanted to hear the machinery operating in their vicinity so they could subjectively tell whether there was a malfunction based on the change in sound[5]. The referenced Goodman paper[5] also discusses additional acoustic issues and considerations encountered though out the history of NASA space craft development.

The CQ rack exterior continuous acoustic emissions requirement is that the levels are not to exceed the NC-40 octave band limits. This requirement is a sub-allocation of the overall Node 2 module to meet NC-50 in which all of the Node’s hardware acoustic spectrums are integrated. Exterior emissions of the CQ rack were assessed using a spatially weighted average calculated from a 14-microphone array that was distributed across the front and sides of the bump-out structure (surface interfacing the Node habitable volume. Although this method has been used before on other ISS rack systems, the CQ is the most complex geometry rack to date to which the array method has been applied. From the measurements, it was determined that the exterior noise level met the NC-40 requirements with the ventilation at the low-speed setting, Fig. 16. This was considered acceptable because the low-speed setting is considered the continuous operating condition. The higher settings are considered intermittent operating conditions that are controllable by the crew member.

The CQ interior sound pressure level acoustic requirements measured at the crew member’s head location are to be greater than NC-25 but less than NC-40. The exterior sound pressure level requirement also only applies at the low-speed ventilation setting. The rational for this requirement is that the crew members control the ventilation speed and can adjust it to suit their personal preference. The lowest ventilation setting is therefore considered the nominal condition for this analysis.

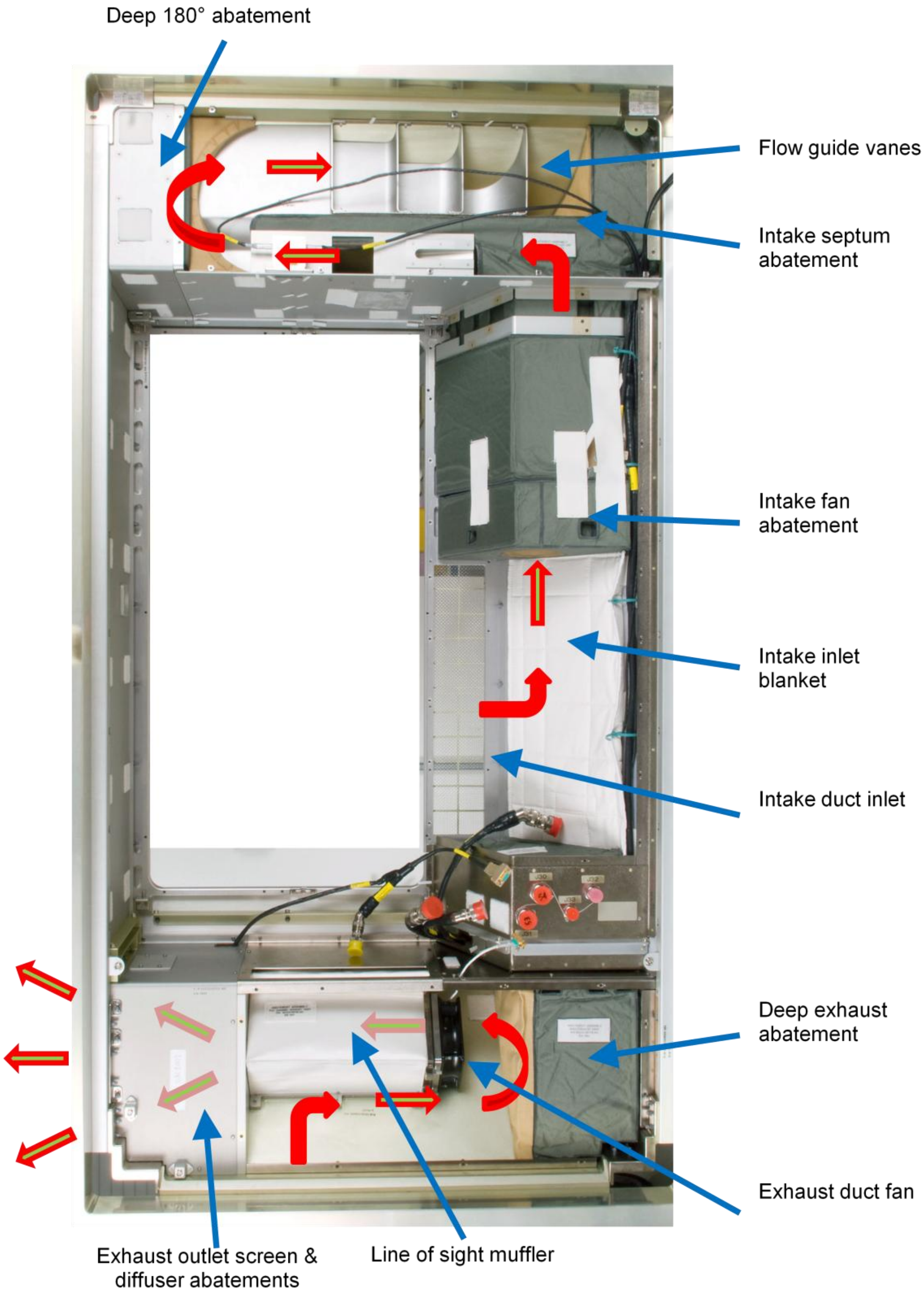

Figure 15. Bump-out interior with acoustic blankets and closeout panels removed to expose ventilation duct acoustic abatements.

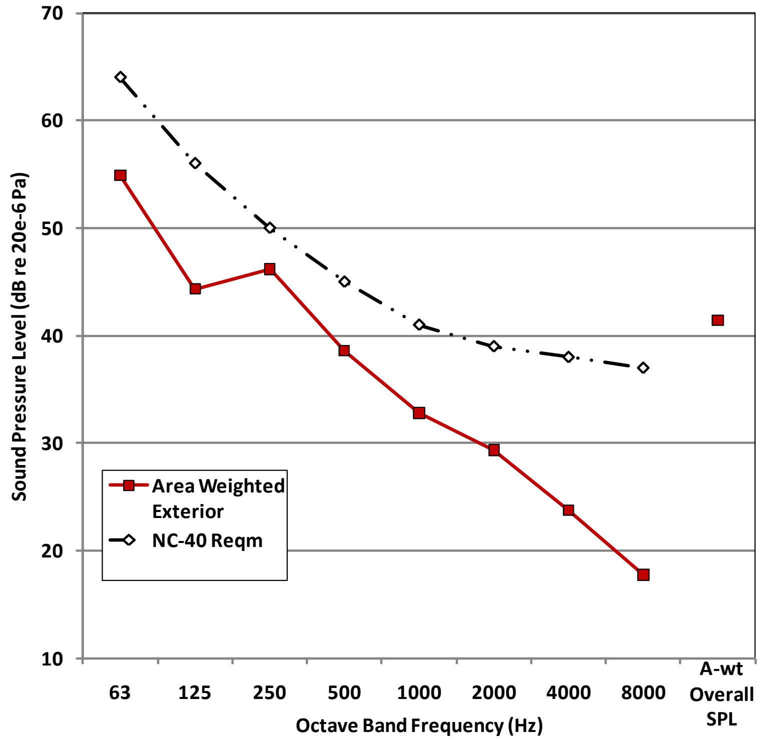

Figure 16. Area weighted average sound level of exterior of the CQ.

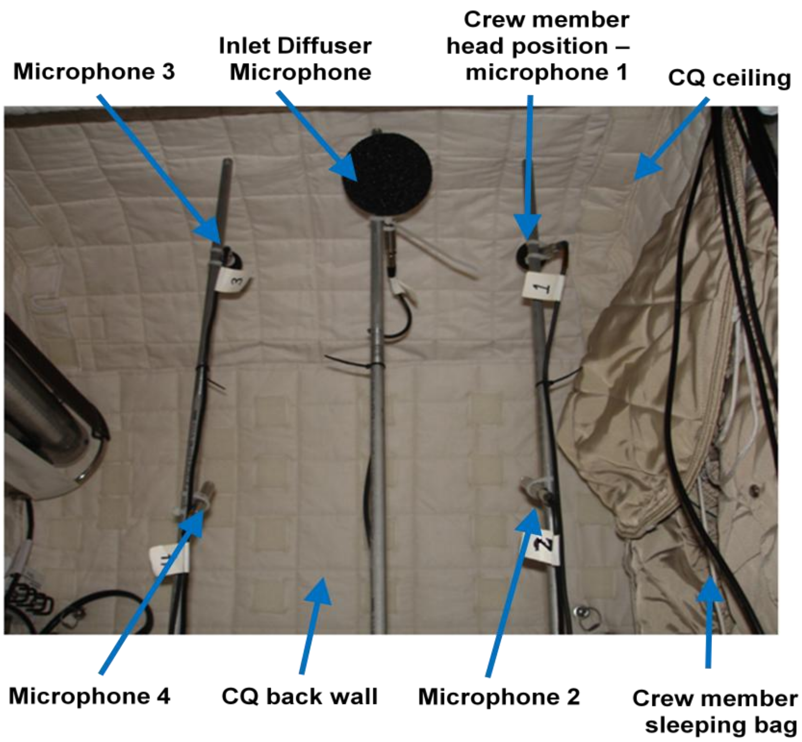

Figure 17. Photograph of the CQ interior 30 cm measurement grid.

the 5th percentile height female. The crew member's zero-g neutral body posture limits head position to within a 10 cm range. The midpoint of this range, which is next to the side wall sleeping bag, was used for the head location measurements.

Although the crew member's head location was the only point dictated by the acoustic requirement, three other interior locations were also used to assess the overall interior sound field of the CQ rack; see Fig. 17.

The octave band sound pressure level measurement results for all four microphone locations are shown in Fig. 18. The acoustic requirement is exceeded in the 250-Hz octave band at the crew member's head location. As the frequency corresponds with the blade pass frequency of the inlet and exhaust fans, this band's levels proved a challenge during the developmental acoustic testing. It is interesting to note the variation of the level of the 250-Hz octave band peak over the CQ volume. The level drops dramatically as the measurement location moves toward the center of the volume. This indicates that the geometry of the interior volume plays an important role in amplification and attenuation of the particular frequency content of an acoustic signal. On the basis of this large variation with measurement location, an exception to the acoustic requirement was granted.

IV. Crew Quarters On-orbit Performance

A. Crew Member Feedback

Since initial CQ installation in December 2008, six crew members have occupied the CQs. Privacy restrictions prevent the delineation of specific crew member comments. However, in general crew member feedback has been very favorable. The crew members have indicated that overall volume, illumination, and stowage of the CQ are acceptable. There have been a few comments about the desire for a few more hook-

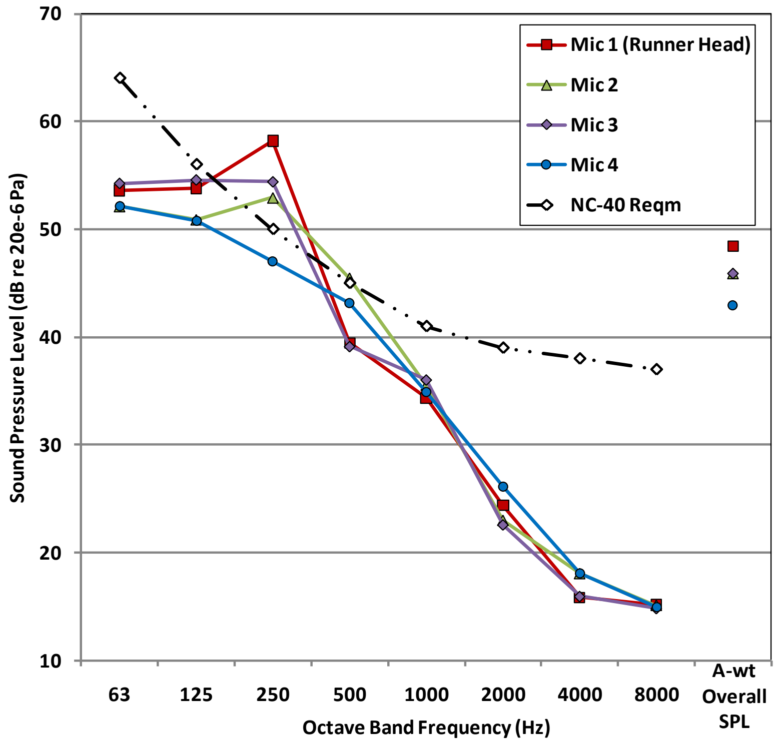

Figure 18. CQ interior sound-level measurements at low fan speed from microphone array.

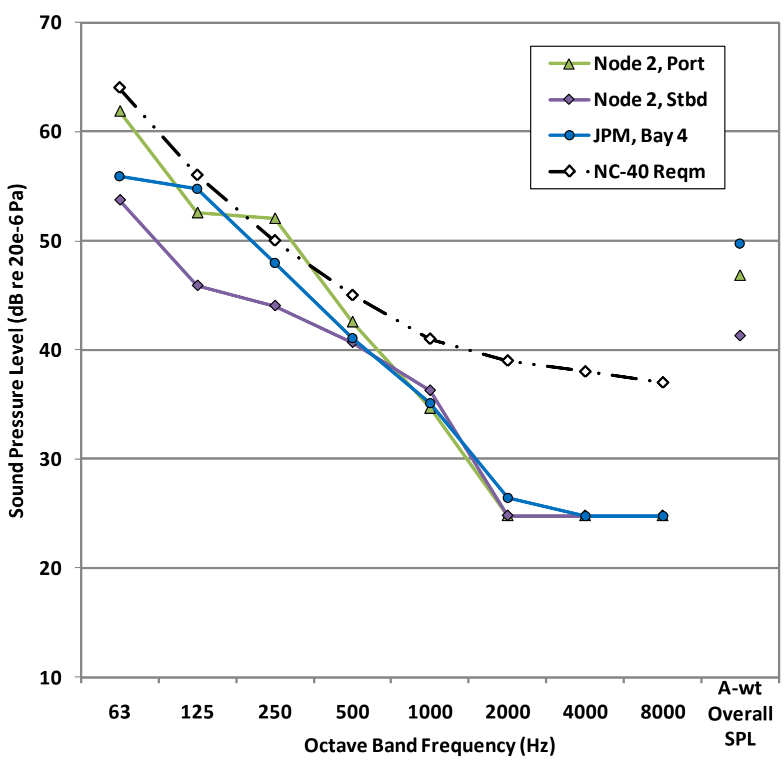

Figure 19. On-orbit CQ interior sound-level measurements at the crew member head location with the fan on low fan speed.

and-loop fastener patches for display or placement of crew items. Adequacy of airflow has generally been acceptable with most crew members reporting that they kept the fan on low or medium speed. Since the interior temperature of CQ is dependent on a combination of the Node 2 CCAA temperature setting and the CQ fan speed setting, there have been times during which one crew member was too warm while others were comfortable. The crew members recognize that the CQ does provide a needed acoustic break from the ISS aisle ways and work areas. The interior does allow a quiet and dark place for sleeping. However, several crew members have commented that the fan's high-speed setting generates a louder acoustic environment than desirable. There are currently no plans to modify the on-orbit CQ flight hardware, but it may be possible to reduce the acoustic noise in the future with either a new quiet fan design or active noise cancellation within the CQ ventilation ducts.

The only on-orbit issue has been the repeated triggering of the starboard CQ single-fan failure alarm. The alarm can be triggered by either the intake or the exhaust duct because the signals are generated if any one of the sensors' trip points are exceeded ("OR" logic gates). Troubleshooting to date has included limited crew member inspection and airspeed readings with a handheld meter in the CQ air outlets. With only limited crew member time available for troubleshooting, it has not been practical to get sufficient data to compensate for the variability caused by the relatively low airspeed and turbulent divergent outlet airflow. Although inconclusive, the leading alarm trigger candidate is that dust has accumulated on both fans and/or flow sensors and reduced the airflow. The CQ interior is vacuumed weekly, including the inlet screens of both the inlet and the exhaust ducts. Lint is reported to be present on the screens during cleaning. Although the fans are cleanable, they are purposely located in the duct interiors and surrounded by acoustic abatements to reduce acoustic noise. The intake fan requires the removal of two panels and one abatement to access. The exhaust fan requires the removal of the anti-blockage net and one panel to access. The initial annual disassembly and cleaning of the CQ fans and ducts was delayed, but the cleaning is currently scheduled in June 2010. Based on this initial cleaning activity the frequency of cleaning will be adjusted to maintain adequate ventilation system performance.

B. Acoustic Measurements

Acoustic measurement surveys of the ISS are conducted bi-monthly. Always of particular interest to these surveys are the sleep locations of the crew members. Due to the short delivery schedule for the CQ racks, it was not possible to perform an acoustic test of the first two racks that were delivered to the ISS in late 2008 on utilization logistics flight 2 (ULF2). The two CQs launched on ULF2 are located in Node 2, Bay 5 port and starboard rack bay locations. However, acoustic certification testing was performed on the CQ rack launched in late 2009 as part of ISS construction mission 17A. The CQ on 17A is temporarily located in the Japanese Pressurized Module (JPM), it is scheduled to be relocated to Node 2, Bay 5, deck location in June 2010. The fourth and last CQ was launched in March and activated in late April 2010 but has not yet had on-orbit acoustic measurements performed.

The CQs in the port, starboard, and JPM locations have been measured repeatedly during the on-orbit sound level measurement surveys. Typical octave-band spectra of the three units measured at the crew member's head location operating at low speed are shown in Fig. 19. Note the blue curve is the acoustic certification rack that was discussed earlier.

The variation among the three on-orbit units is somewhat surprising, as well as the relatively low sound pressure levels on-orbit as compared to those of the ground test. There are several possibilities for the variations among units and the ground testing. First, the microphone location is not as well controlled on-orbit as it is in the laboratory. The crew member performing the measurement is simply asked to place the microphone in the crew member's head sleep position and take the measurement. Second, some variation was noted during ground testing based on the assembly of the CQ structure and abatements. Since the racks were assembled on orbit on different occasions by different crew members, it is not unexpected that some variation among the acoustics of the racks would be noted. Finally, the decrease in levels as compared to the CQ ground testing is attributed to the deployment of crew member's personal effects (e.g., clothing) inside the rack. Acoustic tests performed during the development of the CQ indicated that the interior sound pressure levels were very sensitive to the volume and absorption of items placed inside. To maintain repeatability, however, crew member items were not accounted for in the certification test as they vary from crew member to crew member. Crew member items that are installed on-orbit can include stowage bags for clothing, pictures, laptop, and other items.

V. Conclusions

In general, the ISS CQs have received favorable crew member comments with respect to acoustics. Some crew member comments have indicated the need for reducing the acoustic signature of fans on high speed. As demonstrated by the CQ hardware, it is possible to reduce noise transmission from the relatively acoustically noisy ISS aisleway to provide a dedicated crew volume that is quiet and private. The use of full-scale functional ventilation/acoustic mockups is critical to successful implementation. However, this paper illustrates that the significant design considerations, testing, and impacts are required to reduce acoustic noise by approximately 12 dBA for a 2.1-m^3 habitable volume. In addition to the development cost for acoustic reductions while providing adequate ventilation, the CQ had to allocate about 5% and 15%, respectively of its total mass and volume. The total impact across all four CQs is approximately 72 kg and 1.2 m^3. This impact is a significant penalty for passive noise cancellation for ISS, which is in low Earth orbit. Future missions at Lagrange points or planetary surfaces can likely not support this level of mass and volume impact. It would therefore be beneficial to reduce noise at its source using advanced, quiet fans and active noise cancellation inside ventilation ducts. This would reduce the ambient acoustic noise of future vehicles and greatly reduce or eliminate the need for passive acoustic measures.

Acknowledgments

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