Baltimore, Maryland
NOISE-CON 2010
2010 April 19-21

Noise Control in Space Shuttle Orbiter

Jerry R. Goodman[1]
Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Code SF22
2101 NASA Road 1
Houston, TX 77058

ABSTRACT
Acoustic limits in habitable space enclosures are required to ensure crew safety, comfort, and habitability. Noise control is implemented to ensure compliance with the acoustic requirements. The purpose of this paper is to describe problems with establishing acoustic requirements and noise control efforts, and present examples of noise control treatments and design applications used in the Space Shuttle Orbiter. Included is the need to implement the design discipline of acoustics early in the design process, and noise control throughout a program to ensure that limits are met. The use of dedicated personnel to provide expertise and oversight of acoustic requirements and noise control implementation has shown to be of value in the Space Shuttle Orbiter program. It is concluded that to achieve acceptable and safe noise levels in the crew habitable space, early resolution of acoustic requirements and implementation of effective noise control efforts are needed. Management support of established acoustic requirements and noise control efforts is essential.

1. INTRODUCTION
Requirements for an acceptable acoustic environment during space operations are discussed in References.[1-3] Limiting the acoustic exposure levels in the crew compartment and habitat is deemed essential to achieve a safe, functional, effective, and comfortable acoustic environment for the crew. Noise control should include defining the plans and efforts needed to achieve compliance with the acoustic requirements. The status and the progress of the noise control efforts need to be actively monitored. Noise control implemented in the Space Shuttle Orbiter (Orbiter) program is discussed. Examples of noise control treatments and design applications used in this program are presented. Focus of this paper is on in-flight continuous noise and covers the noise control activities from the start of the related Orbiter hardware development in 1973 until the time this author left the Orbiter Project Office, in 1995.

2. NOISE CONTROL STRATEGY
Crew compartments in space hardware are confined volumes with closed-loop environmental systems that usually involve significant hardware systems and equipment for life support, thermal control, crew sustenance, mission and vehicle operations, and survivability. The resultant environment is challenging from an acoustics standpoint because of the different sound sources, the relatively restricted volume for crew operations and rest/sleep, and the design and operational repercussions of controlling the acoustics environment. The energy emitted from the

[1] Email address: jerry.r.goodman@nasa.gov

sound sources follows various paths into the crew compartment. The acceptability of the resultant acoustic levels at the crew receiver location is established by the requirements for the habitable environment. Unwanted sound is defined as noise. Noise control is the application of designs and technologies necessary to limit the noise at the source, along its path, and at the receiver location to acceptable levels.[4,5] Examples of noise control and applications will be addressed at these locations and along these paths.

A noise control plan needs to be developed and implemented to ensure compliance with the established acoustic limit requirements. It is important to actively monitor the status and the progress of the noise control plan to ensure good communications on efforts, to identify the areas of emphasis and/or concerns early in the design process, and to allow timely remedial actions.

It is especially important that noise control be incorporated at the earliest possible time in the design and development cycle. In the Spacelab program (1983-1998), where 20 dB of noise UHGXFWLRQ□DW□□□□□□□+]□ZDV□UHTXLUHG□□LW□ZDV□UHSRUWHG□WKDW□³,W□F for future noise control programs that noise control should be incorporated at the very earliest GHVLJQ□VWDJH□´□(TXLSPHQW□SRVLWLRQLQJ□IRU□6SDFHODE□ZDV□QRW□RSWLPL]H noise abatement was not considered early enough in the program.[6]

In the Orbiter program, noise control was implemented on the major noise sources only after very high levels were evident and problematic. Noise control was stifled well into the program because: (1) the resolution of the initial requirements was slow; (2) the continuous acoustic limits were set as goals instead of requirements; (3) the final limits were established very late in the program; and (4) remedial actions were not pursued when analyses showed significant exceedances in the required limits.

Most acoustic problems in the International Space Station (ISS) occurred as the result of the lack of emphasis or focus on meeting the defined requirements, on performing insufficient noise control in the early stages of the design and development, and/or the late verification testing with an unacceptable remedial recovery time.

As the design and the development continue in a space vehicle program, the noise control options are more restricted and the impacts of making changes are more significant or even prohibitive.

3. SPACE SHUTTLE ORBITER

Continuous acoustic noise requirements were originally requested (1973) to be at a limit of NC-50 (58.1 dBA) for work conditions and NC-40 (49.0 dBA) for sleep, to conform to the NASA acoustic standard.[7] +RZHYHU□□1$6$¶V□FRQWUDFWRU□GLG□QRW□FRQFXU□WKDW□WKHVH or should be met because they thought the limits were excessively stringent and would have a major impact on design.[8] The NC-50, NC-40, and other Noise Criteria (NC) curves are shown in Figure 1.

In 1974, the contractor agreed to NC-55 (62.6 dBA) as a design goal for work and as a requirement for sleep. Note that the dBA levels used in this paper are for overall, A-weighted levels and dB levels are not weighted. Later, in 1975, NC-55 (62.6 dBA) was accepted as a work and sleep requirement, but was not accompanied by any significant hardware changes or efforts to ensure that this requirement could be met; and at this time in the program, it was getting late to do so. In 1977, predicted levels for the first flight Orbiter vehicle were 77.5 dBA for the mid-deck and 70.0 dBA for the flight deck.[9] Assessments of possible remedial actions were made, but no major action to resolve specification exceedances was approved for implementation because of cost and schedule impacts. In summary, specification levels were not resolved until late in the program, and noise control efforts until this time were limited to those discussed in the section below under path control.

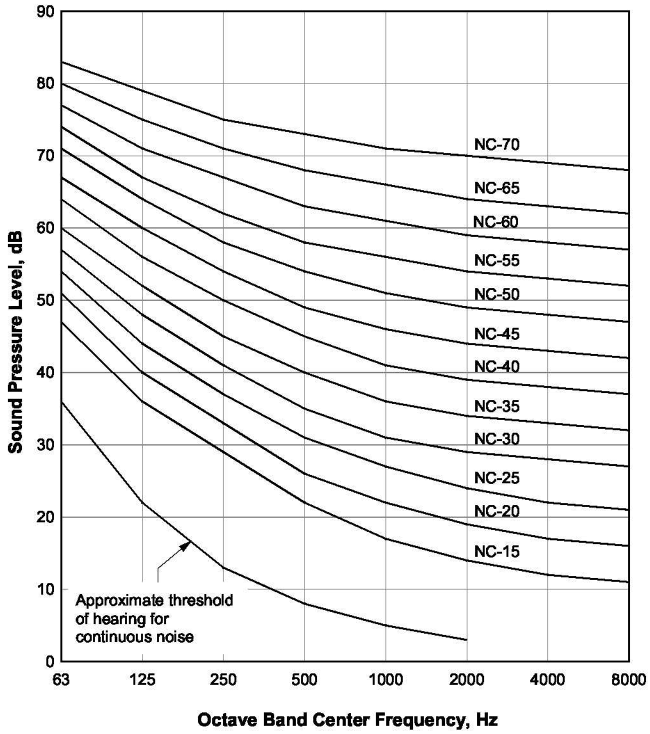

Figure 1: Noise Criteria (NC) curves.

A. Source Control

Primary noise sources in the Orbiter are the fans, water pumps, water separators, avionics, and smoke detectors. There are five closed loop fan cooling systems in the Orbiter: a cabin atmospheric revitalization system; an inertial measurement unit (IMU) cooling system; and three avionics bay cooling systems. These air cooling systems are shown in Figure 2.

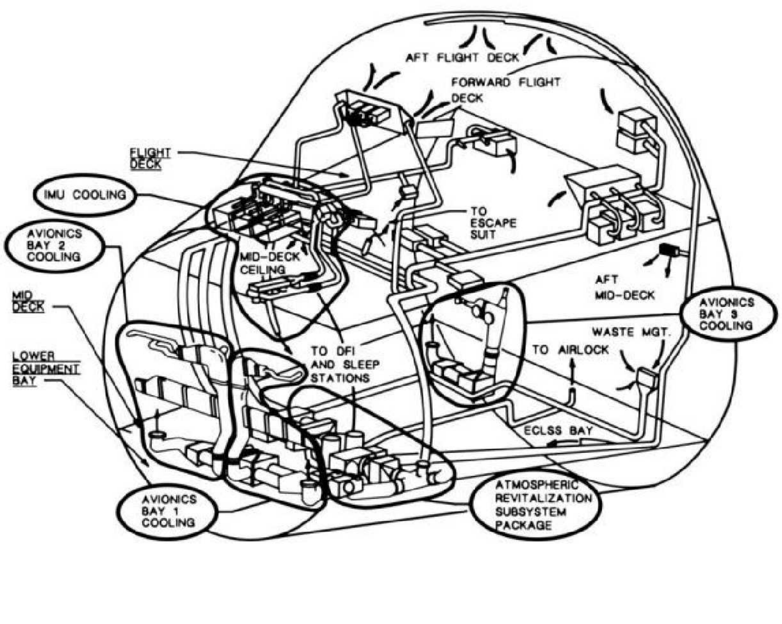

Figure 2: Orbiter cabin air and avionics bays air cooling systems.

It was felt important to develop quiet fans and pumps for the Orbiter because of problems with controlling the noise of this hardware in Apollo. Before the Orbiter contract was awarded, NASA had a program with an aerospace company to develop quiet fans and guidelines for quiet fans and pumps, which successfully demonstrated techniques to control the noise from this KDUGZDUH□□8VH□RI□WKH□TXLHW□IDQ□WHFKQRORJ\□ZDV□SXW□LQWR□WKH□6SD statement-of-work. Initially, the quiet fan approach was used by the contractor as a design baseline. Later another fan was chosen that was closer to meeting overall fan performance requirements, and had less overall cost and schedule impacts.

B. Path Control

The important acoustic modifications and efforts made during the development of the Orbiter were: the addition of vibration isolators to the mounting fixtures of all the fans and pumps; the testing of all fans, pumps, and other items to determine their sound power emissions; and the addition of acoustic barrier material to the closeouts in each of the three avionics bays to block noise coming into the cabin (Figure 2). The vibration isolator assembly is shown in Figure 3.

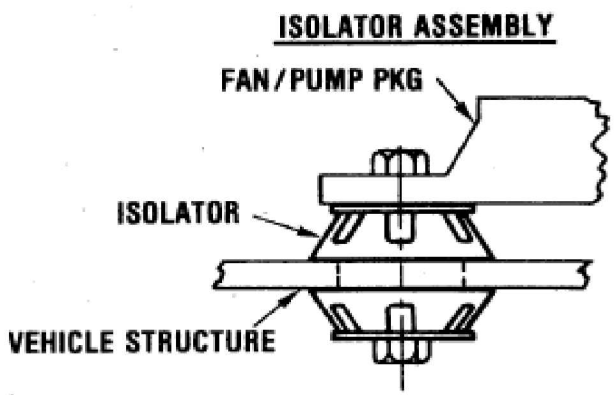

Figure 3: Typical Orbiter vibration isolator assembly.

In 1977, implementation of mufflers in various cabin air cooling loop ducting was investigated to mitigate the predicted high noise levels for the mid-deck and flight deck and was brought to an Orbiter Project Configuration Control Board for disposition.[9] These provisions were not approved because of cost and schedule impacts.

No further remedial actions were pursued to address the acoustic levels until high levels were measured at the first Orbiters pre-delivery tests at Palmdale, California in early 1979 (data are not available). These levels were reviewed and determined to be unacceptable by acoustics representatives. Astronauts who listened to the full-up system levels confirmed that the acoustic levels were very irritating and unacceptable, and that remedial action was necessary. As a result, mufflers were developed and added to the Orbiter IMU cooling system (Figure 2), which was until then the loudest noise source. The mufflers were provided as Government Furnished Equipment (GFE) and consisted of three inlet and one outlet muffler, the design of which is shown in Figure 4.

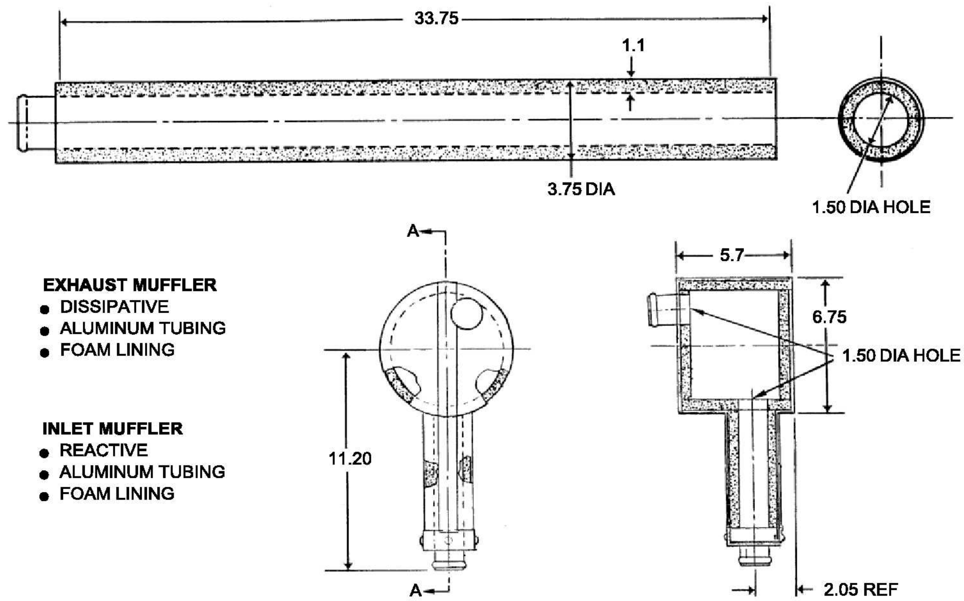

Figure 4: Orbiter Government furnished equipment (GFE) inertial measurement unit (IMU) cooling fan mufflers.

The acoustic benefits for the use of the GFE foam lined reactive and dissipative muffler designs[10] are shown in Figure 5.

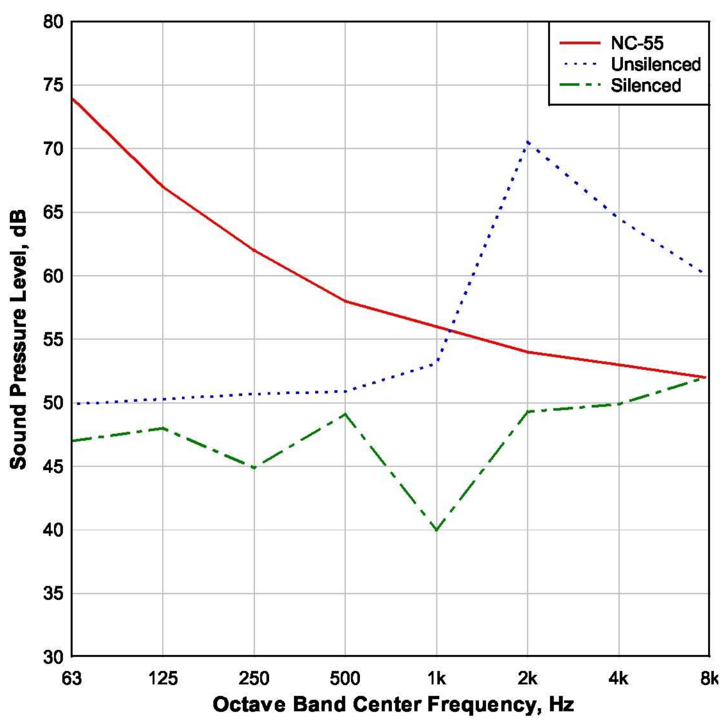

Figure 5: Orbiter inertial measurement unit muffler attenuation.

Testing performed at Kennedy Space Center in 1980, after these mufflers were installed, identified the individual acoustic source contributions on both decks, as shown in Figure 6.[10] Resultant acoustic levels were 67.5 dBA for the mid-deck and 63.5 dBA for the flight deck.[11] The emerging dominant noise source in both decks was the cabin fan. The IMU fan levels were significantly reduced at 2,000 Hz, showing the benefits of the added mufflers in reducing the mid-deck acoustic spike at this frequency. The measured mid-deck levels making up this all systems curve was adopted as the mid-deck specification, and the flight deck all systems measured levels were adopted as the specification values for the flight deck.

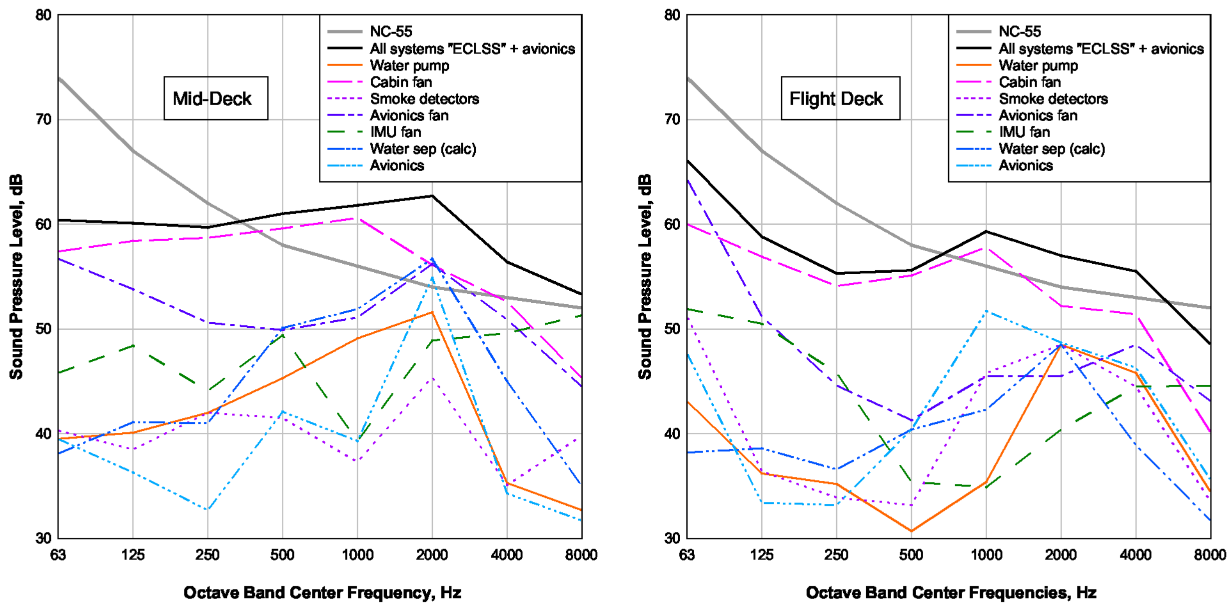

Figure 6: Individual source contributions on the Orbiter mid-deck and flight deck, measured at the specification locations.

These GFE IMU mufflers subsequently were changed from the four individual mufflers to one unified muffler with four chambers having similar functions, to provide an improved line replaceable unit. There were several path related changes performed later in the program: in 1990 a muffler was added to the Regenerative Carbon Dioxide Removal System that was used in extended duration Orbiter missions which began in 1992,[12] and in 1992 covers were approved for large holes in the mid-deck floor, large slots in the avionics bay 3A, and numerous depressurization holes in closeout panels.[13]

Although the IMU mufflers were the only early noise control measures applied to the airborne air cooling path ways, testing was performed to determine the attenuation provided by the ducting, as shown in Figure 7.

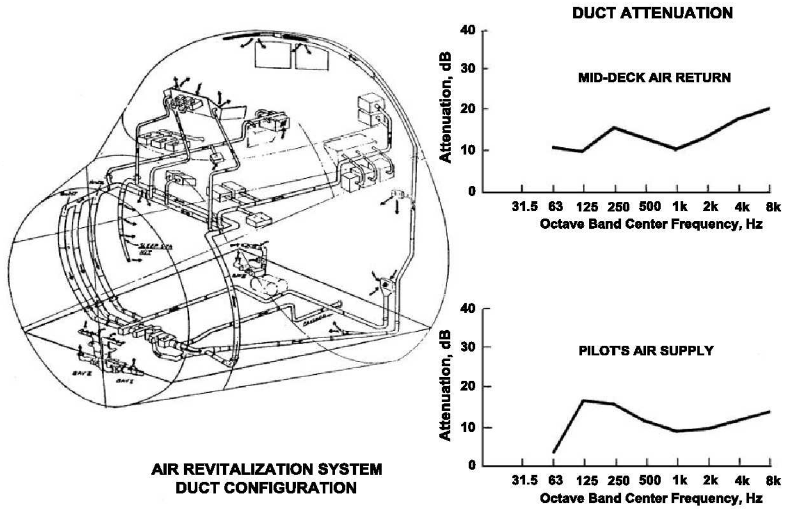

Figure 7: Orbiter airborne noise path air duct attenuation.

C. Noise Control at the Receiver Location

The only noise control provisions made at the receiver location dealt with sleeping accommodations. Originally, the crew slept in sleeping bags affixed to structure attachments in the mid-deck (Figure 8). Accordingly, the sleeping crew was exposed to mid-deck acoustic levels, except for when they were wearing the provided hearing protection.

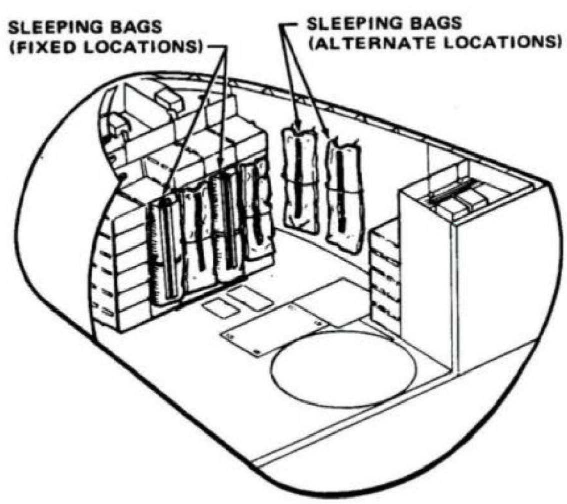

Figure 8: Orbiter sleeping bags in mid-deck.

When dual shift operations occurred, a sleeping three tier plus one vertical bunk was manifested that accommodated a crew of four, as shown in Figure 9.

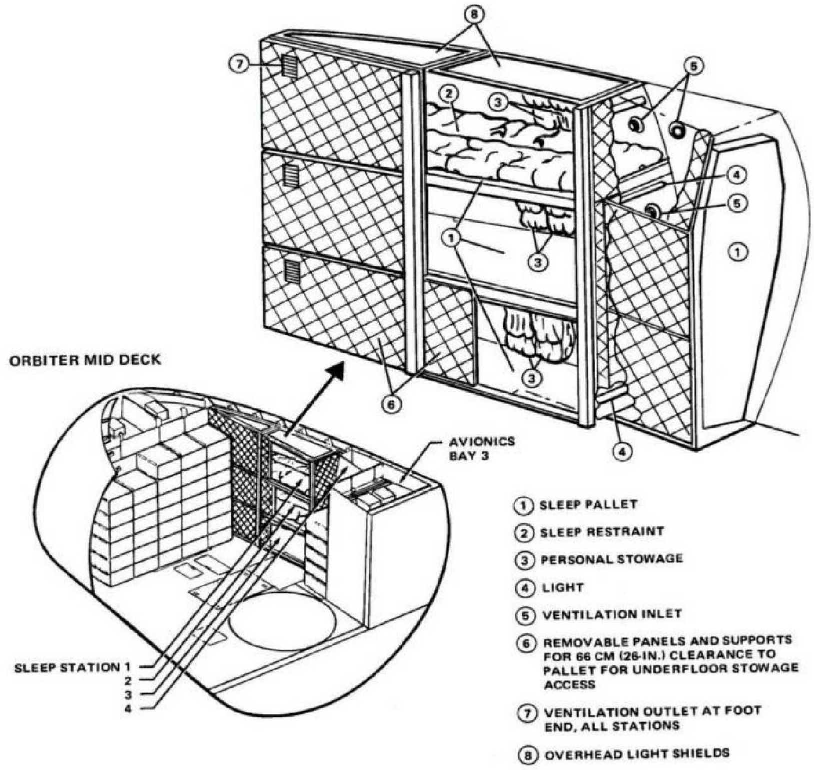

Figure 9: Three-tier plus one vertical sleeping bunk.

The one vertical position bunk created operational problems because the area was not very well isolated and its location was a problem because on-duty crew needed access to stowage lockers in that vicinity. Measured acoustic levels in one of the horizontal bunks were 57 dBA.[10] This sleep station was subsequently changed to provide for a four-tier sleep station where all four of the crew slept parallel to each other, occupying the same volume as the three-tier bunk (Figure 10). Later, covered foam acoustic liners were added in each bunk to lower the on-orbit acoustic levels to meet the desired NC-40 levels.

Figure 10: Four-tier sleeping bunk.

4. DISCUSSION OF THE NOISE CONTROL EFFORTS

Some fundamental noise control provisions were implemented to manage the noise in the Orbiter such as: isolators to support fans and pumps; sound power testing of noise sources; analyses of predicted levels; and barriers to block noise emitted from the three avionics bays. Except for these changes, noise control efforts were minimal. This was due to the problems previously discussed with resolving acoustic requirements and the impacts of remedial changes. This was also affected by both the NASA and the contractor management not considering acoustics a significant enough concern to merit impacts predicted. Several attempts to implement more effective noise control and an effort to apply the NASA standard of NC-50 were unsuccessful. Late definition of proposed remedial actions created severe impacts.

When the high acoustic levels found at Palmdale were discovered, technical personnel and astronauts who witnessed final acoustic testing helped provide an impetus to fix the high level acoustic noise from the IMU fans. Noise control efforts were quickly sanctioned by management. The resultant Orbiter mid-deck levels were well above the NC-55 requirement, but they would have been much higher had not the IMU cooling system been quieted. There was also a basic lack of timely testing to verify that the flight test Orbiter complied with the limits (NC-55) in place, and little time to make acoustic changes without significant design impacts. The Orbiter did not comply with its NC-55 mid-GHFN□UHTXLUHPHQW□□DOWKRXJK□LQ□WKH□I the operational vehicles, without payloads, were found to have mid-decks which ranged in levels from 62 dBA to 65dBA. This was lower than the 67.5 dBA measured previously[11] for the mid deck, due to changes from flight test to the operational configuration where there were more closed out areas and other configuration changes, and later in 1992, when various holes were covered.

After the STS-40 mission in June 1991, specification levels in the Orbiter mid-deck and flight deck were modified to the levels shown in Figure 11 (International Space Station (ISS) specifications NC-52, NC-50 and NC-48 are shown for reference). For this modification the worst case levels measured in both the mid-deck and the flight deck were used from testing performed on the first flight test Orbiter, after the IMU muffler was installed.[14] The intent was to have one specification for both decks. The limit curve shown in Figure 11 is equivalent to 68 dBA. Payloads installed after the first few flights added to the existing noise levels. To minimize the impacts on the overall system levels, the payload complement levels were restricted to 10 dB below the overall limit of each deck, or to 58 dBA for the mid-deck and 53 dBA for the flight deck. In 1991, when the Orbiter specification limits were changed to make mid-deck and flight deck the same (68 dBA), payload complement limits on both decks were modified to be 10 dB lower, or 58 dBA.

Another important aspect of noise control during development of the Orbiter and early missions was the acoustics personnel involved from the contractor and NASA. The contractor had a competent acoustics point of contact in their Structures and Dynamics group who oversaw modifications, developed acoustic plans, performed testing and analyses, and worked with sub-contractors and design groups on internal acoustic efforts. Noise control features implemented in the crew compartment were well designed and implemented. A good summary of this work is documented by Hill.[10] Some aspects of Orbiter noise control are also discussed by Hill[15] and Goodman.[16]

NASA acoustics consisted of one part-time Crew Compartment Project Engineer who was the lead for acoustics in the Orbiter Program and the chair of an Acoustics Working Group (AWG). The AWG consisted of representatives from the NASA Johnson Space Center (JSC) Astronaut office, Space and Life Systems Directorate, Crew Systems Division, Structures and Mechanics Division, Mission Operations, Communications, Acoustic Testing laboratory, and others. The AWG met periodically to review requirements, status, provided a means to integrate inputs from their respective organizations, and served as a JSC advisory group to the Chairman. Several briefings were made to the Orbiter Project Configuration Control Board, attempting to get the requirements resolved and noise control efforts started and supported. Since GFE crew equipment and payloads testing were performed at a JSC laboratory, some insight into the GFE and payload hardware acoustic problems were uncovered early, but, in general, remedial actions and consulting were very limited.

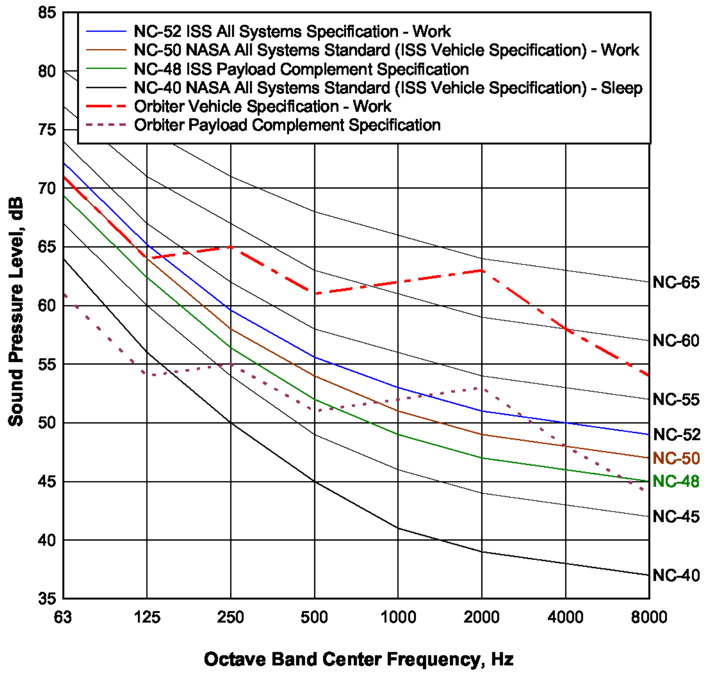

Figure 11: Noise Criteria (NC) curves, Orbiter and International Space Station (ISS) specifications, and NASA standard.

After initial flights, payloads became a major challenge in maintaining overall specification compliance. Significant efforts were spent in ensuring that the payloads and their complements met their requirements for each mission. These efforts were essentially successful, although there were occasions where the requirements were waived and problems were created, such as for the STS-40 mission and others.[16] Discussions of Orbiter acoustics efforts and an assessment of Orbiter acoustics from a mission standpoint are discussed by Goodman.[14]

5. CONCLUSIONS

Implementing effective noise control measures was hampered by problems with the timely resolution of what acoustic limits to apply. Acoustic limits should be "designed in," starting in the early stages of the design phase of the vehicle. Establishment of acoustic requirements and noise control efforts were affected by contractor and NASA management attitude towards acoustics and late projected contractor impacts. Acoustic verification was not performed until the first spacecraft was at Palmdale undergoing final checkout, which was very late to take remedial actions. The NC-55 requirement was significantly exceeded for the work environment, but was met for sleep conditions.

7KH□ QRLVH□ FRQWURO□ HIIRUWV□ LPSOHPHQWHG□ E\□ 1$6$¶V□ FRQWUDFWRU□ Z
1$6$¶V□WHFKQLFDO□OHYHO□RI□DWWHQWLRQ□WR□DFRXVWLFV□DQG□QRLVH□FRQWU
oversight of noise control efforts and payload acoustic compliance.

The lessons learned from Orbiter acoustics and noise control efforts were to resolve and implement acoustics requirements early in the development of a manned habitable spacecraft, and pursue noise control early in the program ensuring compliance with the requirements. A noise control plan should be established which includes analyses, the testing of hardware and the proposed noise control measures. Full-up systems tests should be conducted early in the program to allow time for remedial measures to be implemented and the program should have dedicated, experienced oversight of the noise control efforts. Finally, it is important that management understands, supports, and sanctions early resolution of requirements and noise control efforts.

6. REFERENCES

[1] Goodman, Jerry R. and Grosveld, Ferdinand W., Acoustics in Habitable Space Vehicles and Enclosures. *Proceedings of the Third IAASS Conference*, Rome, Italy, 21-23 October 2008.

[2] Goodman, J.R. and Grosveld, F.W., Part I - Space Environment (Natural and Induced) - Acoustics, S*afety Design for Space Systems*, Ed. Gary Musgrave, Axel Larsen and Tommaso Sgobba, Elsevier Publishing Company, 2008.

[3] Smith, Suzanne D., Goodman, Jerry R., and Grosveld, Ferdinand W., Vibration and Acoustics, *Fundamentals of Aerospace Medicine*, 4th edition, Jennifer A. Fogarty, Jan Stepanek, Robert Johnson, Jeffrey R. Davis, editors, Lippincott Williams and Wilkins, USA, 2008.

[4] Grosveld, Ferdinand W., and Goodman, Jerry R., Noise Control in Habitable Space Vehicles and Enclosures, *Proceedings of the Third IAASS Conference*, Rome, Italy, 21-23 October 2008.

[5] Goodman, J.R. and Grosveld, F.W., Part III ± Noise Abatement Design, S*afety Design for Space Systems*, Ed. Gary Musgrave, Axel Larsen and Tommaso Sgobba, Elsevier Publishing Company, 2008.

[6] Eilers, D., Wyn-Roberts, D. and Borches, I. Audible Noise Control in Spacelab ± as Part of Manned Spacecraft Environmental Control. ESA Spacecraft Thermal and Environmental Control, 1978, pp 301-317.

[7] MSC Design and Procedural Standard, Design Standard 145, Acoustical Noise Criteria, NASA Manned Spacecraft (MSC), 16 October 1972.

[8] Letter 73MA2110, from Smith, Edward P., Chief Program Engineer Space Shuttle Program to National Aeronautics and Space Administration, 9 April 1973.

[9] Goodman, J.R., Cabin Acoustical Noise Criteria and Design Implementation. Presented to the Orbiter Configuration Control Board, July 1977.

[10] Hill, R.E., Space Shuttle Orbiter Crew Compartment Acoustic Noise - Environments and Control Considerations. Report 94SSV154970. Rockwell International, Houston, Texas, 1994.

[11] Silveira, Milton, Results of OV-102 Acoustical Noise Test at NASA Kennedy Space Center. Memorandum from MA/Manager, Orbiter Project, 1 July 1980.

[12] Crew Module Acoustic Noise Control for EDO Missions Equipment. Approved at the Orbiter Configuration Control Board, 2 October 1990.

[13] Goodman, J.R., Crew Module Acoustic Noise Control for EDO Missions. Approved at the Orbiter Configuration Control Board, May 26, 1992

[14] Goodman, J.R., New Acoustical Noise Control Requirements for the Space Shuttle Program. Briefing to the Space Shuttle Program Control Board, November 1993.

[15] Hill, R.E., Space Shuttle Crew Module Prior Noise Reduction Efforts. Presentation to the Acoustical Noise Working Group, NASA Johnson Space Center, Houston, Texas, 1992.

[16] Goodman, J.R., Acoustics Inside the Space Shuttle Orbiter and the International Space Station. Proceedings of SAE 2009 Noise and Vibration Conference and Exhibition, St. Charles, Illinois, 2009.