N94-11538

Noise Levels and their Effects on Shuttle Crewmembers' Performance: Operational Concerns*

Anton S. Koros (LESC), Susan C. Adam (NASA), and Charles D. Wheelwright (LESC)

Lockheed Engineering and Sciences Company
2400 NASA Rd. #1 / MS-C95
Houston, TX 77058

NASA-Johnson Space Center
Mailstop-SP34
Houston, TX 77058

ABSTRACT

When excessive, noise can result in sleep interference, fatigue, interference with verbal communication and hearing damage. Shuttle crewmembers are exposed to noise throughout their mission. The contribution of noise to decrements in crew performance over these extended exposure durations was the focus of this study. On the STS-40/SLS-1 mission noise levels were evaluated through the use of a sound level meter and a crew questionnaire.

Crewmembers noted that sleep, concentration, and relaxation were negatively impacted by high noise levels. Speech Interference Levels (SILs) calculated from the sound level measurements suggested that crewmembers were required to raise their voice in order to be heard. No difficulty detecting caution and warning alarms was noted.

The higher than desirable noise levels in Spacelab were attributed to flight specific payloads for which acoustic waivers were granted. It is recommended that current noise levels be reduced in Spacelab and the Orbiter Middeck especially as longer missions are planned for the buildup of Space Station Freedom. Levels of NC 50 are recommended in areas where speech communication is required and NC 40 in sleep areas. These levels are in accordance with the NASA Man-Systems Integration Standards. Measurements proposed for subsequent orbiter missions are discussed.

INTRODUCTION

STS-40, with its payload of Spacelab Life Sciences-1 (SLS-1), was the fourth mission to fly the Spacelab module. However, it was the first mission completely dedicated to studying the physiological changes which occur in the human body when it is exposed to the microgravity of space. STS-40 was launched aboard Space Shuttle Columbia on the fifth of June, 1991. Along with a variety of medical studies Detailed Supplementary Objective (DSO) 904 Human Factors Assessment of Orbiter Missions was manifested. This DSO concentrated on the issues of tunnel translation; noise; vibration; task timelining; stowage, deployment and cable management. The results of the study on noise and the implications for future flights will be presented here.

Noise is defined as <u>unwanted</u> sound. The effects of noise on human performance have been well documented. Excessive levels of noise can result in a number of consequences, including permanent threshold shift (PTS), temporary threshold shift (TTS), interference with verbal communication and/or sleep, annoyance, irritability, and fatigue. In a survey of 33 Shuttle astronauts, Willshire and Leatherwood (1985) reported that more than half of the respondents found that noise disturbed their sleep. In addition, almost half experienced speech interference.

All manned space missions rely upon crewmember performance and so the consequences of excessive noise levels can hold severe implications for mission success. Therefore, noise limits have been imposed. These limits are usually expressed in A-weighted decibels (dB A). Leo Beranek (1988) explains that "the A-weighting of a sound level meter discriminates against sound pressure signals at frequencies below 1000 Hz and above 6000 Hz, and enhances levels between 1000 Hz and 6000 Hz." This scale is used because it approximates human perception.

The acoustic requirements for the Orbiter are presented in Section 3.4.6.1.3. of the Orbiter Vehicle End Item Specification (OVEI) (NASA, 1986), while for Spacelab the levels are contained in the Spacelab Payload Accommodations Handbook (SPAH) (NASA, 1985), Section 5.1.1.4.1. Currently the noise limits are 63 dB A on the Orbiter Flightdeck, 68 dB A on the Orbiter Middeck, and 59 dB A in Spacelab. Originally, the noise limits for both the

* Results previously presented at 123rd Meeting of the Acoustical Society of America 11-15 May 92, Salt Lake City, UT.

Orbiter and Spacelab were specified as NC 50 (56 dB A); however, due to implementation costs these limits were increased.

Before STS-40 flew, acoustic waivers were sought for several mission specific payloads including the Animal Enclosure Modules (AEM's), ergometer, and Orbiter Refrigerator/Freezer (OR/F). These waivers were granted with the understanding that the noise levels would be monitored to ensure hearing protection would be utilized if levels exceeded 76 dB A.

The objective of this portion of DSO 904 was to interpret crewmembers' subjective comments on the effects of noise during the STS-40 mission based on two objective measures—inflight sound level measurements and pre- and postflight audiometry results. It was anticipated that crewmembers would find the noise levels during sleep periods intrusive, and that when noisy payloads (such as the treadmill and vacuum cleaner) were operating noise levels would interfere with verbal communication. Subjective information was primarily sought to assess existing requirements. A secondary objective entailed determining if current noise levels impacted crew task performance.

Data presented in the Man-Systems Integration Standards (NASA, 1989, p 5-44) suggests that temporary threshold shift (TTS) can occur when noise levels exceed 75 decibels on the linear scale. Levels during STS-40/SLS-1 were expected to approach this level, and it was therefore suggested that the hearing threshold of individual crewmembers might be affected.

With the crews' consent, the flight surgeon provided audiometric data so that a statistical analysis could be performed to determine if crewmember's hearing thresholds were higher upon completion of the mission than ten days prior to lift off. It was also hypothesized that the frequencies tested with the audiometer would be affected to varying degrees, dependent upon the make-up of the acoustic environment.

Ward (1962) determined that recovery from noise exposure is generally complete within 24-48 hours. However, audiometric tests typically are not conducted on crewmembers until 3 days after landing—several hours after the anticipated recovery period has passed. Therefore, the Flight Surgeon's Office requested that arrangements be made for the audiograms to be taken as soon as possible after landing of STS-40.

Six measurements of the acoustic environment were made and stored on a one-third octave sound level meter. Since the measurements were intended to be estimates of the overall background noise level experienced by the crewmembers, and the environment was highly reverberant, the measures were taken in the center of each area (Middeck, Flightdeck and Spacelab) with the sound incidence correction factor set to 'diffuse'. Subjective evaluations of the acceptability of the sound levels were interpreted on the basis of objective measures.

METHOD

Subjects

The seven crewmembers assigned to the STS-40/SLS-1 mission participated in the evaluation. The crew consisted of four males and three females.

Apparatus

Questionnaire. The degree to which noise impacts an individual can be assessed by determining the degree to which the following occurred—annoyance, speech interference, or the need for implementation of hearing conservation techniques. Hearing conservation techniques include the use of earplugs, earmuffs and other protective devices. Post-flight questions were selected to assess each of these dimensions.

The postflight questionnaire consisted of 14 forced choice questions each with a five point rating scale. Questions fell into one of three categories—need for improvement, frequency of occurrence, or concurrence. Crew were also encouraged to provide comments on specific experiences. The comments collected via the postflight questionnaire were explored in greater detail in person with the crew during the postflight debrief.

Sound Level Meter. The sound level meter used was a Brüel & Kjær Type 2231 Sound Level Meter (Serial Number 1575194), B & K Octave Filter Set Type 1625 1/3-1/1 (Serial Number 1581549) and B&K Microphone Type 4155. The B & K Loudness Calculation Module BZ 7111 was loaded to enable the meter to measure and store ten one-third octave spectra. This sound level meter was selected because it required minimum preflight training and inflight time, was highly versatile, met the weight and volume restrictions, was similar to the Orbiter sound level meter that had already passed space qualification tests, and measured and stored one-third octave band data.

Audiometer. Both pre- and postflight audiometry measurements (consisting of air conduction screenings) were gathered by the Flight Surgeon's Office (Johnson Space Center) using Tracor audiometer Model RA400. The

Hearing Level for each crewmember at seven selected frequencies was received for both sets of measurements. Hearing Level refers to the difference in decibels between the threshold of the person being tested and the standardized audiometric zero (the average threshold of young individuals with no hearing impairment) at that frequency.

Procedures

Three months before launch a briefing was held with the STS-40 crewmembers to sensitize them to the issues to be investigated during the human factors evaluation. At five weeks to launch the questionnaire was submitted to the crew for content and procedure evaluation and two of the crew were trained to take the inflight sound level measures. The audiometric data was gathered by the Flight Surgeon's Office prior to and upon completion of the mission.

During the mission, DSO 904 personnel at Johnson Space Center monitored audio and video downlink to capture additional crew comments.

RESULTS

Questionnaire

Crewmember responses to the postflight questionnaire were received from the crew within three weeks of landing. In response to the questions of whether noise had interfered with their ability to concentrate, or to relax one individual in each case stated that interference had 'Never' occurred. Neither individual represented a Payload Specialist and therefore their duties did not restrict them to the Spacelab. Six of the seven crewmembers also found that noise interfered with their ability to relax. Three stated it had occurred frequently, and one found that noise always interfered with their ability to relax. One crewmember found that their ability to relax was never affected by noise.

Sound Level Meter

The evaluation called for ten one-third octave measurements to be made and stored by the crew; however, due to operational and time constraints only six were taken. Sound level measurments were made at the following locations and environmental conditions:

1) Center of the Middeck with the Orbiter Refrigerator/Freezer (OR/F) off and the Animal Enclosure Modules (AEM's) on;
2) Center of the Middeck with the OR/F and AEM's off;
3) In Middeck one foot from the AEM's while the AEM's and OR/F were operating;
4) Center of the Flightdeck during nominal operations;
5) Center of the Spacelab while one Spacelab Refrigerator /Freezer (R/F) compressor was operating; and,
6) In Spacelab, four feet from Spacleab R/F's while both compressors were running.

Figures 1 and 2 show the sound level measurement data graphed against the NC 50 curve. This U.S. Noise Criteria Standard has been included on the graphs to allow comparison with "acceptable" noise levels.

The DSO 904 measurements were taken during nominal operations; when levels would be expected to be at their minimum. This appears to be the case since the overall time weighted average noise level was 75.5 dB A on Flight Day 6 according to the dosimeter manifested by the JSC Orbiter Engineering Office.

This evaluation concentrated on the measurements made near the center of the acoustic spaces because they are believed to be the most representative of noise levels to which the crew was exposed. As one moves closer to the walls in a reverberant environment, such as in the Shuttle, sound level measurements double due to the pressure doubling effect at "hard" surfaces. Therefore, the measurement made one foot from the AEM's will not be included when describing the 'average' acoustic environment. This measurement (number 3) cannot be considered an accurate determination of whether the payload exceeds the applicable payload specification since the measurement includes the noise emitted by the source and the Orbiter ambient background noise level.

Audiometer

Audiograms were taken approximately an hour and a half after landing. Mean hearing level on the audiogram across crewmembers (and frequencies) prior to the mission was 8.52 decibels compared to 12.86 decibels afterwards. An analysis of variance comparing individual crewmembers pre- and postflight hearing levels on the audiometer suggests that hearing thresholds were statistically higher postflight than preflight, $F(1,6) = 5.27$, $p < .0242$.

An analysis of variance comparing the frequencies tested in the audiogram indicated that individual frequencies were effected differently, $F(1,6) = 6.69$, $p < .0001$. The Student-Newman-Keuls test confirmed that changes at the 6,000 and 8,000 hertz frequencies were significantly different from the changes that occurred at the 1,000 and 2,000 hertz frequencies.

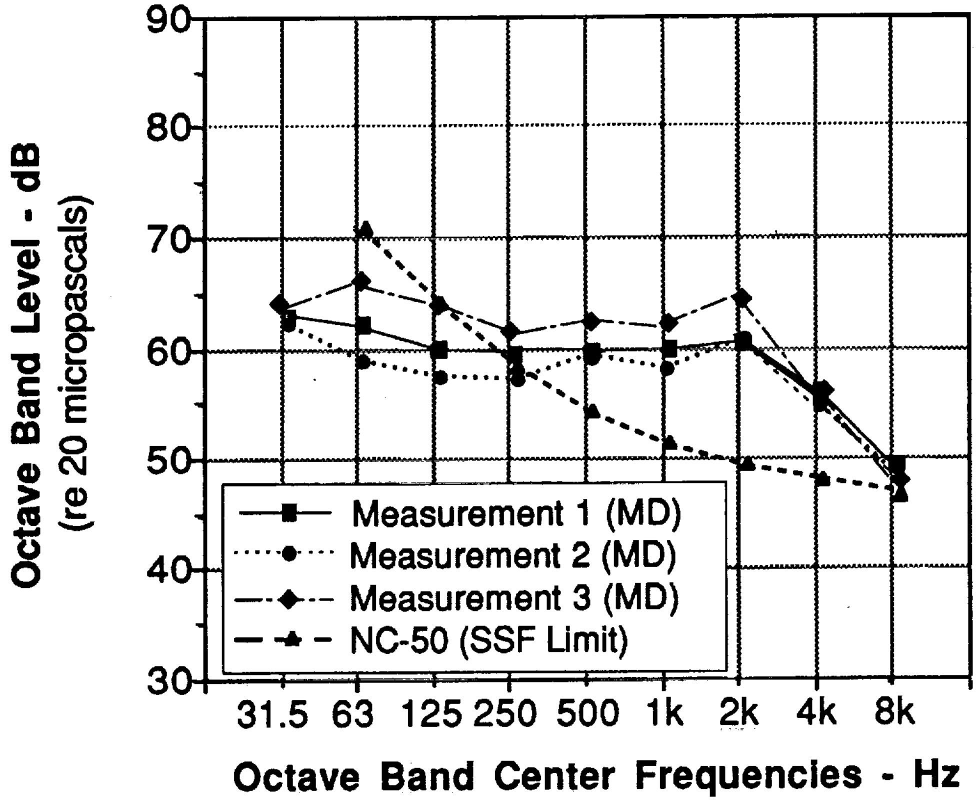


Figure 1. STS-40 Middeck noise measurements.

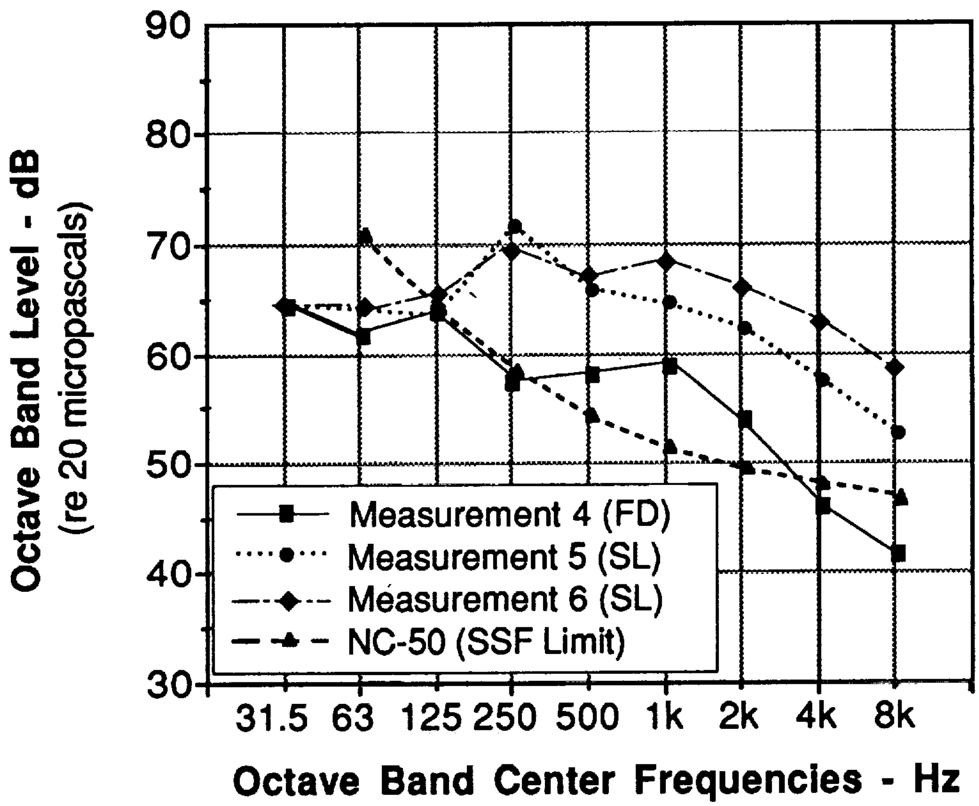


Figure 2. STS-40 Flightdeck and Spacelab noise measurements.

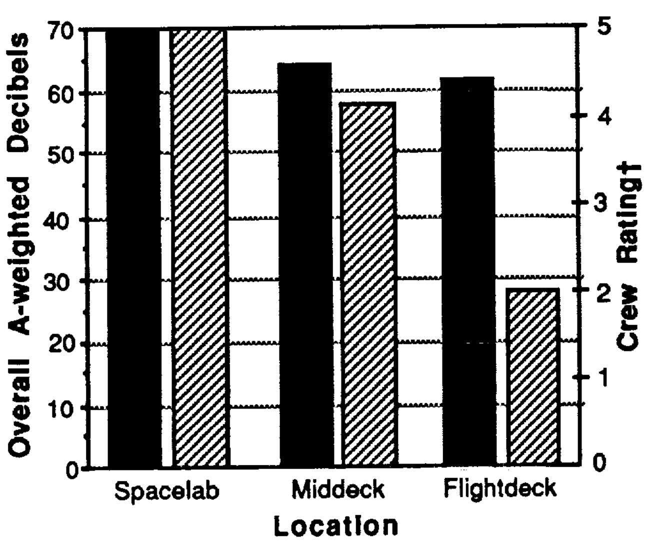
DISCUSSION

Overall noise levels

Although human reaction to noise is highly individualistic, a great deal of consistency was evident among rankings of the acceptability of noise levels by the STS-40 crew. Overall, reductions in noise levels were suggested for Spacelab and for specific pieces of equipment in the Middeck. No such recommendations were made in regard to the Flightdeck.

Crewmembers were asked to rate noise levels (based on their perception of the need for improvement) in each location. The areas perceived as louder by the crew did prove to be louder when measured with the sound level meter; see Figure 3 for comparison. Measurements made near the center of Spacelab were higher than those made near the center of the Middeck—the arithmetic averages being 70.1 and 63.85 dB A respectively. The Flightdeck was perceived as the quietest area and when measured it did receive the lowest value (61.8 dB A). These values reflect the average ambient noise level for each area during nominal operations based on the sound level measurements conducted during this investigation.

It is apparent from Figure 3 that for relatively small increases in noise level (as measured in A-weighted decibels) the perceived need for improvement increased dramatically. Especially



†5=Improvements Mandatory, 4=Improvements Necessary, 3=Improvements Desirable, 2=Improvements Possible, 1=Improvements NOT Needed

Figure 3. Average sound level and crew rating by location.

noteworthy is the crew's discrimination between the Orbiter Middeck and Orbiter Flightdeck. Although there was only a two decibel difference in measured levels between the two areas, the crew stated that improvements (decreases) in the noise level of the Middeck were 'necessary'; while in the Flightdeck, improvements were rated as 'possible'. Noise is measured on the log scale and although a 3 decibel increase is equivalent to a doubling in intensity, Woodson (1981, p. 849) indicates that human listeners find a 3 decibel increase in noise levels barely perceptible. Therefore the difference in the crewmembers' perception of the two areas appears to be due to spectral differences in the makeup of the environments.

Comparison of the frequency spectra from the Middeck and Flightdeck measurements indicates that while levels are similar at most frequencies, at 2000 hertz the levels on the Middeck were higher than those on the Flightdeck. Since man is more sensitive to noise in the frequency range between 250 hertz and 2000 hertz the crew's rating of the Middeck as being more in need of improvements is consistent with data from the sound level meter measurements. Furthermore, the frequencies at which the Flightdeck was higher (31.5, 63 and 125 hertz) fell outside of this range. Spectra like those on the Middeck would also be more likely to result in annoyance and speech interference.

The entire STS-40 crew agreed that current noise levels would be unacceptable for longer duration missions. This supported the comments previously made that reductions in noise levels were mandatory for Spacelab during the current 9-day mission. The crewmembers suggested that the noise offending equipment should be "fixed". One individual felt that without these improvements crewmembers on longer duration missions may have to resort to periodically turning off offenders to reduce the noise.

Sleep Interference

Responses to the postflight questionnaire indicate that sleep interference was prevalent, even though ear plugs were used. Six crewmembers wore ear plugs at night and each recommended that noise levels be reduced during sleep periods—four of them believed the reductions to be mandatory.

Annoyance

When particularly loud noise sources such as the ergometer, treadmill and vacuum were operating, crewmembers found it harder to focus and they experienced difficulty relaxing.

Interference with the ability to concentrate was reported by six of the seven crewmembers. Three found that it had taken place frequently. One of the astronauts stated that noise was particularly bothersome in Spacelab when "coordination with other crewmembers was required."

Responses to the statement that "noise became increasingly bothersome" suggest that this dimension also varies greatly between individuals. Three of the crewmembers agreed that noise was more bothersome later in the mission, while one did not. The remaining three crewmembers were undecided. It appears that depending on the individual, continued noise can be, but is not necessarily, more bothersome.

This varied response across crewmembers is likely due to their individualistic response to noise. The threshold at which noise is considered to 'interfere' varies by individual—particularly with respect to the ability to sleep, concentrate and relax. This suggests that the amount of annoyance experienced by an individual cannot be predicted based upon the physical parameters of the noise environment alone.

Speech Interference

The crew noted that verbal communication was hampered by the noise levels. It was especially bothersome when the treadmill, ergometer, or vacuum cleaner were operating. As one crewmember said, it was necessary "to shout to nearby crewmembers during ergometer operations in the Spacelab, or speak at an uncomfortable level when at opposite ends of the Spacelab." Another comment addressed the consequences of such interference—noise "disrupted communications continuously requiring repeats and misunderstood instructions."

The extent to which speech interference takes place can be determined by evaluating the frequency range between 300 hertz and 6,000 hertz. The Speech Interference Level (SIL) was calculated for the DSO 904 measurements based on the American National Standards Institute (1977) standard. This standard defines the SIL as the average unweighted noise levels of the octave band center frequencies at 500, 1,000, 2,000, and 4,000 hertz. The SIL's for the two measurements taken in the center of the Middeck were averaged, as were the two Spacelab SIL's.

The DSO 904 measurements were made during nominal operations and therefore are considered to represent the best case scenario. Using a figure derived by Beranek (1988,p.559), the distances required between male and female speakers and listeners for satisfactory speech communication can be derived. For STS-40 this approach predicts that for astronauts speaking in a normal voice to communicate effectively they would have to be within approximately 0.6 meters (2 feet) of each other in the Flightdeck, 0.5 meters (1.6 feet) in the Middeck, and 0.2 meters (0.65 feet) in Spacelab. This may not present as significant a problem in the Middeck (or Flightdeck) since it is a relatively small area; however, Spacelab was 7 meters (22.97 feet) long and crewmembers were required to operate workstations separated by large distances and therefore non-aided communication in this environment would be extremely difficult.

In such an environment, individuals raise their voice to compensate—often without being aware of it. This increased vocal effort contributes to fatigue. Crew comments suggest that this did occur during STS-40. One crewmember stated regarding noise, "it was a major, if not the major contributor to fatigue."

Temporary Threshold Shift

Statistical analyses confirmed that the 4.34 dB increase in average postflight hearing threshold (across crewmembers and frequencies) over preflight was statistically significant. The greatest increases in hearing level occurred at 500 and 6,000 hertz, and were 7.86 and 6.78 dB respectively. Although the reliability of repeat audiograms is high, it should be noted that additional variance between the scores is likely to have occurred since testing conditions during both measurements could not be held constant due to operational constraints. Postflight audiometry data was gathered in California near the landing site—a different acoustic environment than during preflight measures.

Recommended Noise Levels

It is apparent that noise levels should be reduced. Allowable levels should be determined based upon the tasks that will be performed. In areas where speech communication is required, the NC 50 criterion is appropriate because above that level speech interference increases dramatically. Pearsons (1975, p. 7) predicted that in the Shuttle, an NC 50 curve would allow nearly 80% of key words to be understood correctly at a distance of five to eight feet. However, as levels increase to the NC 55 level, the percent of key words understood correctly drops to near 30%.

The NC 50 curve was originally adopted as the background noise criterion onboard the Shuttle during on-orbit conditions. The limit was subsequently increased to the existing standards due to the programmatic cost of compliance.

Beranek, Blazier, & Figwer (1971) suggest that background noise levels not exceed 47 dB A (equivalent to the NC 40) for sleeping, resting, and relaxing.

Current acoustic standards delineated for Space Station Freedom in the Man-Systems Integration Standards, Volume IV (NASA, 1989, p 5-44) specify the NC 50 curve for background noise levels in work areas where voice communication is required, and the NC 40 in sleep areas.

Data From Other Missions

Noise levels on Spacelab Life Sciences-1 (STS-40) were higher than for other missions on which acoustic data have been collected. Eilers (1987) states that during the STS-9 / Spacelab-1 mission, crewmembers found the general noise level of Spacelab to be low, and that on-orbit noise measurements supported this, with an overall noise level of 64 dB A being measured. In contrast, SLS-1 crewmembers found noise levels in Spacelab unacceptable, and background noise level measurements indicated the noise levels to be 70 dB A. The measurements made during the current DSO were taken during nominal operations when levels would be expected to be at their minimum. According to the dosimeter manifested by the JSC Orbiter Engineering Office the overall time weighted average noise level for Flight Day 6 was 75.5 dB A.

Preliminary results from measurements made during a subsequent flight of DSO-904 aboard the STS-50 / USML-1 mission indicate that noise levels were again much lower. In Spacelab during nominal operations (i.e. periods when only the life support and other essential systems are operating) average noise levels were about 62 decibels compared to the near 70 decibel levels measured during SLS-1. Crew comments also reflect a much improved noise environment.

CONCLUSIONS

The higher noise levels on SLS-1 appear to be directly attributable to mission specific equipment—a premise supported by the large number of acoustic waivers which were granted for the SLS-1 mission. While crew comments collected about the noise environment aboard SLS-1 are not representative of all Spacelab missions they provide valuable information about the impact of the acoustic environment on crew satisfaction and productivity.

Further evaluation of the Orbiter acoustic environment and its impact on crew operations is planned--the sound level meter has been manifested to fly again on both SpaceHab-01 and -02 missions due to launch during 1993.

ACKNOWLEDGEMENTS

This research was supported by the National Aeronautics and Space Administration under contract NAS9-17900.

REFERENCES

1. Beranek, Leo L., NOISE AND VIBRATION CONTROL, Washington, DC: Institute of Noise Control Engineering, 1988.
2. Beranek, L. L., Blazier, W. E., and Figwer, J. J., "Preferred noise criterion (PNC) curves and their application to rooms", JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 50, 1971, p. 1227.
3. Eilers, D. "Audible noise control for pressurized modules PM4 and PM2", TECH REPORT COL-MBER-000-TN-0420-1, European Space Agency: MBB/ERNO, 1987.
4. NASA , MAN-SYSTEMS INTEGRATION STANDARDS, VOLUME IV (NASA-STD-3000), Houston, TX: National Aeronautics and Space Administration, 1991.
5. NASA , MAN-SYSTEMS INTEGRATION STANDARDS, VOLUME I (NASA-STD-3000), Houston, TX: National Aeronautics and Space Administration, 1989.
6. NASA , ORBITER VEHICLE END ITEM SPECIFICATION (OVEI) (MJ070-0001-1c), Houston, TX: National Aeronautics and Space Administration, 1986.
7. NASA, SPACELAB PAYLOAD ACCOMMODATIONS HANDBOOK (SLP 2104), Houston, TX: National Aeronautics and Space Administration, 1985.
8. Pearsons, Karl S., RECOMMENDATIONS FOR NOISE LEVELS IN THE SPACE SHUTTLE (Job Number 157160), Houston, TX: Bolt, Beranek, and Newman Inc, February, 1975.
9. Ward, W. D. , "Damage-risk criteria for line spectra", JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA, 34, 1962, pp. 1610-1619.
10. Woodson, Wesley E., HUMAN FACTORS DESIGN HANDBOOK, New York: McGraw Hill, 1981.
11. Willshire, Kelli F. and Leatherwood, Jack D., SHUTTLE ASTRONAUT SURVEY, Langley, VA: National Aeronautics and Space Administration, 1985.