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VIBRATION EXPOSURE CHARACTERIZATION AND HEALTH RISK ASSESSMENT OF THE MH-65D DOLPHIN

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14. ABSTRACT

This study characterized and assessed aircrew vibration during operation of the MH-65D Dolphin owned and operated by the Coast Guard Helicopter Interdiction Tactical Squadron (HITRON) located at Cecil Field, FL. The study was part of a collaboration between the Army Public Health Center and the Air Force Research Laboratory, and was funded by the National Defence Center for Energy and Environment. The ISO 2631-1: 1997 was used as the guideline for the assessments. Triaxial accelerations were collected at the floor/seat base, seat pan and seat back interfaces, and helmet (pilot only) at the pilot, copilot, gunner, and swimmer stations. Data records were collected by aircraft task and associated flight test conditions. All stations showed a major spectral peak in all three directions at approximately 23.5 Hz that was associated with the blade passage frequency of the aircraft. A smaller primarily vertical peak was also observed around 6 Hz that was associated with the propeller rotation frequency. At the pilot helmet, the vertical peak around 6 Hz could be quite substantial, depending on the flight test conditions. Based on the ISO 2631-1 guidelines, comfort reactions primarily ranged from being "a little uncomfortable" to "fairly uncomfortable". Based on the seat pan point vibration total value (ISO 2631-1), the level flight vibration was associated with the potential for health risk in less than 8 hours of daily flight operation at all stations; the lowest exposure durations and highest weighted vibration levels occurred at the highest airspeed (140 KIAS), except at the mid cabin gunner station. The copilot and swimmer stations showed decreases in the exposure durations with increasing airspeed. Health risks were likely in less than 8 hours at the swimmer station at the highest airspeed (140 KIAS). In summary, the results of this study further support the substantial influence of operational vibration on the discomfort and pain that has been associated with the operation of rotary-wing/tilt-rotor aircraft.

15. SUBJECT TERMS Human vibration, helicopters, health risk assessment, discomfort

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PREFACE

This report summarizes the vibration exposure assessment conducted on the MH-65D Dolphin owned and operated by the United States Coast Guard (USCG) Helicopter Interdiction Tactical Squadron (HITRON) located at Cecil Field, FL in accordance with the International Organization for Standardization (ISO) ISO 2631-1 (1997) Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements, ISO 2631-1 Amendment 1 (2010), and the Military Standard MIL-STD-1472G Department of Defense Design Criteria Standard, Human Engineering (2012). The study is part of the project entitled “Operational Vibration Assessment and Database Project 2: Expanded Flight Test Program. Project 2 was funded by the National Defense Center for Energy and Environment (NDCEE). Three additional platforms were targeted for the expanded test program; the UH-60L Blackhawk, CH-47F Chinook, and UH-1N Huey helicopters. The test program included the development of a database quantifying operational vibration and active aircrew subjective perceptions and integrated into the Air Force Collaborative Biomechanics Data Network (CBDN) managed by the 711 HPW/RH. The database will be made available to researchers, equipment designers, and standards developers for establishing effective near- and far-term pain and injury mitigation strategies. A Memorandum of Agreement (MOA) between the Army Public Health Center (APHC) and the Air Force Research Laboratory (AFRL) 711 Human Performance Wing (HPW), Airman Systems Directorate (/RH) was established that set forth the terms and conditions that the two organizations would use to conduct the project with funding from the NDCEE. The AFRL 711 HPW/RH prepared all required documentation including a Flight Test Plan (FTP), and conducted all required review boards including the Technical Review Board (TRB) and Safety Review Board (SRB), in accordance with Air Force Research Laboratory Instruction (AFRLI) 61-103, Scientific Research and Development, AFRL Research Test Management (2015).

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The APHC and AFRL thank the USCG HITRON for their support of flight tests aboard the MH-45D Dolphin, in particular, the assistance and guidance of Alexis D. Scott, LT, USCG.

The APHC and AFRL thank the NDCEE for their financial support of this project.

1.0 SUMMARY

This study characterized and assessed aircrew vibration during operation of the MH-65D Dolphin helicopter located at the USCG HITRON, Cecil Field, FL. The ISO 2631-1: 1997 and MIL-STD-1472G were used as the guideline for the comfort and health risk assessments. The study is part of a larger test program that includes additional aircraft platforms. The specific objectives of this study are:

1. Collect multi-axis acceleration data to characterize the vibration affecting the aircrew and interface equipment aboard the MH-65D Dolphin helicopter.
2. Assess the comfort and health risk of the vibration exposures in accordance with existing human vibration standards.
3. Enter acceleration data into the AFRL 711 HPW/RH Collaborative Biomechanics Data Network (CBDN).

The study was a collaboration between the APHC and the AFRL 711 HPW/RH and was funded by the NDCEE.

Four portable battery-powered data acquisition units (DAUs) were used to collect accelerations at the pilot station (right side), co-pilot station (left side), gunner station (mid-cabin center) and swimmer (aft-cabin right side). Triaxial accelerometer packs were attached to the floor or base of each seat. Triaxial acceleration pads were placed on top of the seat pan and seat back cushions at all stations and locations. A triaxial accelerometer was also attached to the top of the pilot helmet to collect triaxial translational accelerations. Data records were collected by aircraft task and the associated flight test conditions, including taxi, takeoff, hovering flight, climb, level flight, turns, descent, approaches, and landing. Data records were also collected for flight test conditions associated with airborne use of force (AUF) tactics. The onboard test conductor, occupying the swimmer station/location, prompted triggering of the DAUs to collect 20-second records once the aircraft was on a targeted condition. The acceleration spectra were estimated at each station/location and measurement site. The overall weighted accelerations were estimated in accordance with the ISO 2631-1. For assessing the ISO 2631-1 comfort reactions, the overall vibration total value (*oVTV)* was calculated as the vector sum of the weighted triaxial seat pan and seat back accelerations. For assessing the ISO 2631-1 health risks, the point vibration total value (*pVTV*) was calculated as the vector sum of the weighted triaxial seat pan accelerations.

For the MH-65D at all stations, measurement sites, and for most flight conditions, a major peak was observed at approximately 23.5 Herz (Hz) and was associated with the aircraft blade passage frequency (BPF). The most substantial peak observed at the respective BPF did not necessarily occur in the vertical direction. Additional peaks were also noted at multiples of the BPF. A smaller peak was observed around 6 Hz and associated with the propeller rotation frequency (PRF). The peak was the highest in the vertical direction. At the pilot helmet, the vertical peak around 6 Hz was more substantial, depending on the flight condition. The pilot helmet vibration was quite damped beyond the vertical peak associated with the BPF.

Comfort reactions associated with the MH-65D exposures primarily ranged from being considered 'a little uncomfortable' to 'fairly uncomfortable' based on the *oVTV*. The least discomfort was associated with the copilot station. The level flight data used to assess health risk via the seat pan *pVTV* indicated that, with the exception of several records at the copilot

station, all other stations showed exposures associated with the potential for health risk in less than 8 hours. The lowest daily exposure durations or highest *pVTV*s occurred at the highest airspeed of 140 knots indicated airspeed (KIAS), with the exception of the gunner station. Decreasing exposure durations were associated with increasing airspeed at the copilot and swimmer stations. In summary, the pilot was exposed to the potential for health risk between 4 and 7 hours at airspeeds ranging from 80 to 120 KIAS, and in 3 to 4 hours at 140 KIAS. The copilot was exposed to the potential for health risk at around 8 hours or longer at 80 and 100 KIAS, between about 5 and 7 hours at 120 KIAS, and between 3 and 4 hours at 140 KIAS. The gunner was exposed to the potential for health risk between about 3 and 6 hours at all airspeeds, excluding several data records that may have been influenced by occupant movements. The swimmer was exposed to the potential for health risks between about 4 and 6 hours at 80 and 100 KIAS, between 2 and 3 hours at 120 KIAS, and in less than 2 hours at 140 KIAS. With the exception of the large variations in vibration observed at the gunner station at 80 KIAS, and the vibration at the swimmer station at 140 KIAS, all occupants would not be exposed to likely health risks for daily flights lasting 8 hours or less.

In summary, the results of the assessments on the MH-65D Dolphin further support the substantial influence of operational vibration on the discomfort and pain that has been associated with the operation of rotary-wing and tilt-rotor aircraft, particularly given the magnitudes of the higher frequency exposures that still resulted in a potential health risk according to the standards and guidelines. The higher frequency characteristics of the vibration do warrant investigation of the mechanisms by which the vibration can cause pain and injury and can lead to the development of more robust discomfort and pain mitigation strategies. These data and similar data collected aboard other platforms should be used to establish appropriate equipment design criteria for mitigating vibration transmission to the occupant and improving comfort, health, and performance.

2.0 INTRODUCTION

Epidemiological surveys have consistently reported that ~85% of the rotary-wing aircrew surveyed has suffered back, leg, or neck pain associated with flying helicopters (Hamon, Healing, Contarino, & Ellenbecker, 2012). Poor posture, inadequate seats, and aircraft vibration have been targeted as contributing factors but their synergies and physiological mechanisms are unknown. The recent Business Case Analysis (BCA) conducted by R Cubed Consulting for the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OUSD ATL), and Office of the Deputy Under Secretary of Defense Installations and Environment (DUSD I&E) (Hamon et al., 2012) emphasized that musculoskeletal pain and discomfort in these aircrew have a significant negative impact on mission effectiveness and mission readiness with an average yearly avoidable cost of $239 M. The strong recommendation in the BCA for improved seating systems cannot be effectively addressed without clear guidelines on exposure effects, seat design, and validation testing. Appropriate science- and technology-based guidelines on exposure, seat design, and validation testing are non-existent, perpetuating the health issues.

The first step is to clearly characterize the actual human multi-axis vibration exposure aboard various rotary-wing/tilt-rotor aircraft to identify the frequency components, acceleration magnitudes, and direction of the vibration entering the occupant at the occupant/vehicle interfaces (typically the seating system). In addition, there are guidelines provided in human vibration exposure standards that can be applied to these data for assessing the health risk and discomfort associated with the exposures (ISO 2631-1: 1997 and ISO 2631-1/Amd1:2010; MIL-STD-1472G, 2012). Comfort and health risk assessments have been conducted on a limited number of rotary-wing/tilt-rotor platforms (Smith, 2005; Smith & Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008). In 2013, the APHC, National Guard Bureau (NGB), and the AFRL 711 HPW/RH conducted a study aboard the HH-60M Medevac and UH-72 Lakota located at the Vermont Army National Guard (VT ARNG) (Smith, Chervak, & Steinhauer, 2014). The equipment and methodology established by AFRL 711 HPW/RH for collecting and analyzing the multi-axis measurements at various occupant stations were used to characterize and compare the vibration occurring throughout mission-relevant flight operations, and to conduct comfort and health risk assessments in accordance with the existing standards. An aircrew questionnaire developed by APHC and the AFRL 711 HPW/RH was distributed to aircrew members at the VT ARNG. The health risk assessments conducted so far have suggested that certain aircrew may be subjected to potential health risks in less than three hours for occupational exposures (Smith, 2005; Smith & Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008; Smith, Chervak, & Steinhauer, 2014). The AFRL has also used these data to recreate the actual stressor environment in controlled laboratory studies that targeted seat component influences, physiological and psychophysical responses, and task performance during simulated prolonged exposures.

This flight test project was an expansion of the previous studies conducted on rotary-wing/tilt-rotor aircraft. The project was funded by the NDCEE. In addition to the MH-65D, flight tests have been completed on the UH-60L, CH-47F, and UH-1N. A technical report has been generated summarizing the results of the flight tests conducted aboard the UH-60L (Smith, Chervak, & Clasing, 2019). The UH-60L was not equipped with the Active Vibration Suppression System (AVSS) that was included on the HH-60M platform to reduce vertical vibration of the airframe. The pilots aboard the HH-60M and UH-60L were both located on the right side of the cockpit with similar seats. While the HH-60M pilot was exposed to vibration levels associated with potential health risk in as little as 4 hours to greater than 8 hours of daily flight, the UH-60L pilot was exposed to vibration levels associated with potential health risk in less than 4 hours of daily flight. One of the final activities of the project was the integration of aircrew operational vibration and associated documentation into the CBDN managed by the AFRL 711 HPW/RH. The goal was to provide an accessible tool to researchers, equipment designers, and standards developers for establishing effective near- and far-term pain and injury mitigation strategies.

The specific objectives of this study are:

1. Collect multi-axis acceleration data to characterize the vibration affecting the aircrew and interface equipment aboard the MH-65D Dolphin helicopter.
2. Assess the comfort and health risk of the vibration exposures in accordance with existing human vibration standards.
3. Distribute the Aircrew Questionnaire Whole-Body Vibration/Discomfort to HITRON flight personnel (separate report).
4. Enter acceleration data and associated documentation into the 711 HPW/RH CBDN.

The primary metric used to characterize and assess operational vibration is the multi-axis acceleration generated at the human/equipment interfaces in the three orthogonal axes. The typical interface is the seating system but may also include the measurement of triaxial accelerations at the aircrew helmet. The interface accelerations are frequency weighted in accordance with the existing exposure guidelines for estimating the comfort reaction and health risk. The survey/questionnaire metrics included subjective ratings and responses on aircrew perception of the vibration, location of symptoms and discomfort, posture, and interface issues.

A MOA between the APHC and the AFRL 711 HPW/RH was established that set forth the terms and conditions that the two organizations would use to conduct the project with funding from the NDCEE. The AFRL 711 HPW/RH prepared all required documentation including a FTP, and conducted all required review boards including the TRB and SRB, in accordance with the Air Force Research Laboratory Instruction 61-103 (2015).

This report focuses on the characterization and assessment of the human-relevant operational vibration during typical missions aboard the MH-65D Dolphin. The aircrew survey results will be presented in a separate report. Subsequent reports will be forthcoming on additional platforms that were included as part of the larger project.

3.0 METHODS AND PROCEDURES

3.1 Aircraft and Measurement Locations

The MH-65D (tail number 6547) is owned and operated by the USCG HITRON located at Cecil Field, FL. The measurement locations targeted included the pilot station located on the right side of the cockpit, the copilot station located on the left side of the cockpit, the flight engineer/gunner station located mid cabin, and the swimmer station located on the right side aft cabin. All stations were occupied during the flight test.

3.2 Equipment, Instrumentation, and Measurement Sites

Four Remote Vibration Environment Recorders (REVERs), developed by the AFRL 711 HPW/RH, were used to collect multi-axis vibration data at the four aircrew stations or locations. Each REVER, illustrated in Figure 1, consists of the following:

1. A 16-channel DAU (Large or Small)
2. Two battery packs (Large and Small)
3. Triaxial accelerometer packs
4. Two triaxial accelerometer seat pads
5. One trigger device
6. Connection/extension cables as required
7. Laptop computer

Specifications for the REVER components, including dimensions and weights, are listed in Table A-1. Each accelerometer pack consisted of three orthogonally-arranged miniature accelerometers embedded in a Delrin® cylinder. Double-sided mounting tape was used to secure the pack to the appropriate site. Triaxial accelerometer pads were used to measure the vibration transmitted to the occupant via the seat pan and seat back in accordance with the ISO-2631-1: 1997 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part I: General Requirements (ISO 2631-1: 1997). The pad consisted of a flat rubber disk with a triaxial accelerometer pack embedded in the center (Figure 1). Double-sided adhesive tape and duct tape were used to secure the pads to the seat cushions or seat cloth. Table 1 lists the aircrew stations/locations and measurement sites targeted for data collection, including the type of instrumentation.

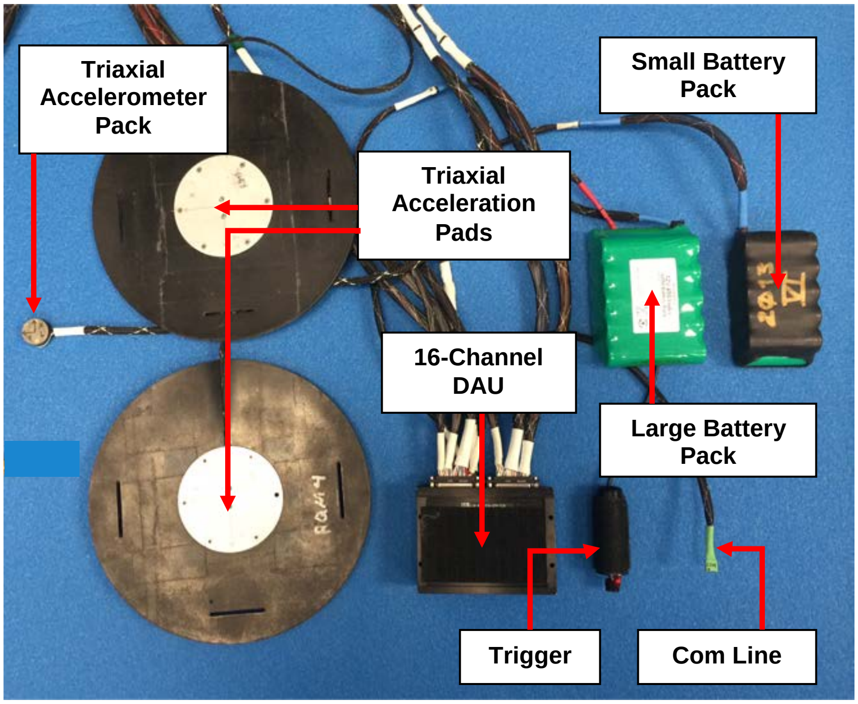

Figure 1. Remote Vibration Environment Recorder (REVER)

Table 1. MH-65D Stations/Locations, Measurement Sites and Type of Sensors

Station	Measurement Site	Instrumentation
Pilot Station (Right Side Cockpit) CBDN Test: MH65DPILOTRIGHT	Lower Left Seat Rail	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
	Helmet	Triaxial Accelerometer Pack
Copilot Station (Left Side Cockpit) CBDN Test: MH65DCOPILOTLEFT	Lower Left Seat Rail	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
Gunner (Mid Cabin, Towards Left) CBDN Test: MH65DGUNNERMID	Cross Bar at back of seat	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
Swimmer (Aft Cabin, Right Side) CBDN Test: MH65DSWIMMERAFT	Floor next to seat	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad

For both the pilot and copilot stations, the DAU and batteries were contained in a small Pelican case secured to the floor on the left side of the mid cabin area (Figure 2). Cables from the DAU were routed to the back of the two stations along the floor. At both the pilot and copilot stations, a triaxial acceleration pad was attached using double-side adhesive tape to the seat pan cushion and seat back cushion (behind the lumbar support) (Figure 3). The cables were routed to the left back side of the seat and connected to the respective DAU cables. All pads and cables were further secured with duct tape. A triaxial accelerometer pack was attached to the top of the pilot helmet using double-sided mounting tape. The pack cable was routed from the helmet to the DAU via an extension cable with a quick release connection (Figure 4). Figure 4 shows the routing and connection of the helmet cable to the respective DAU cable. The helmet pack was further secured with duct tape to prevent any snags.

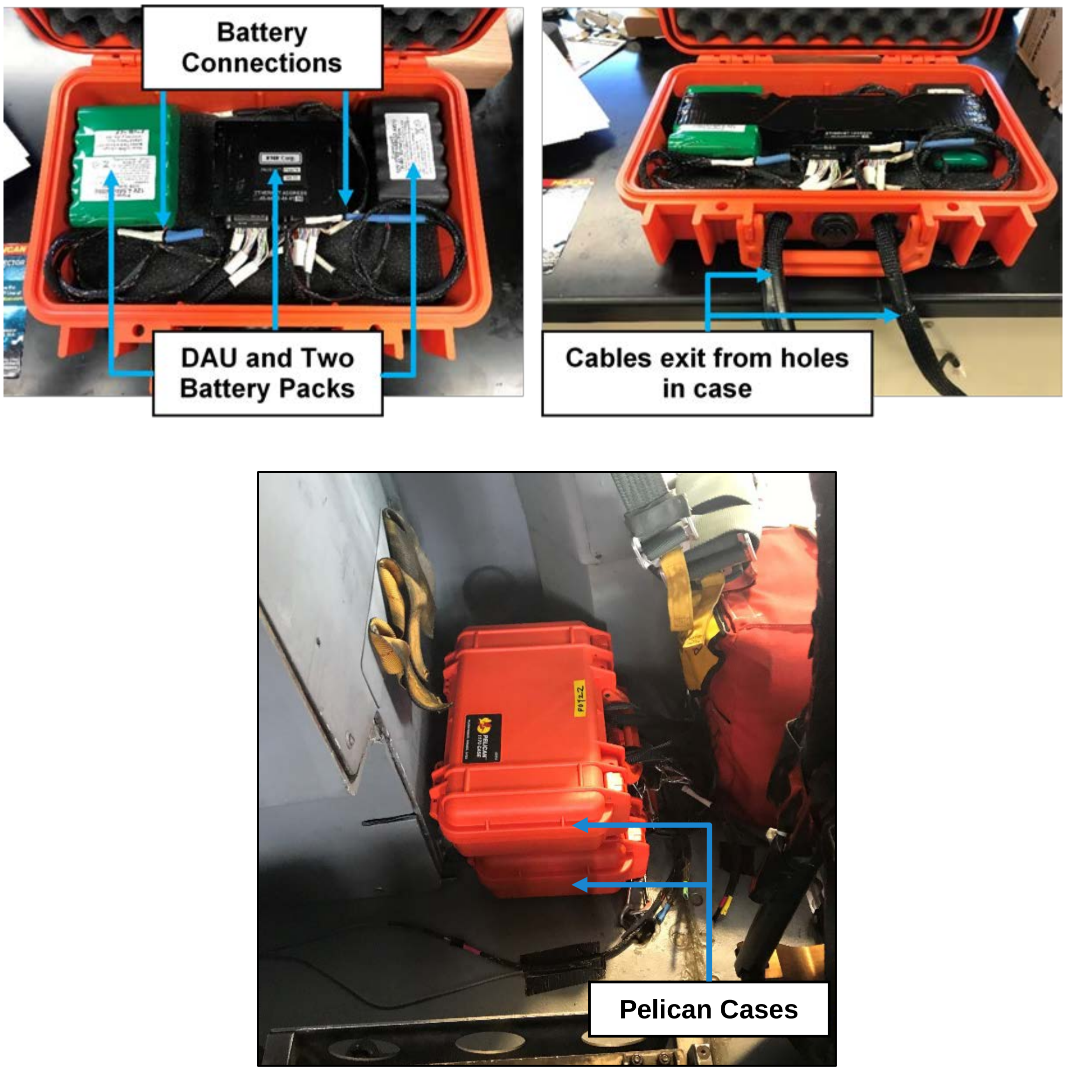

Figure 2. One DAU and two battery packs contained in small Pelican case for measuring at Pilot/Copilot stations

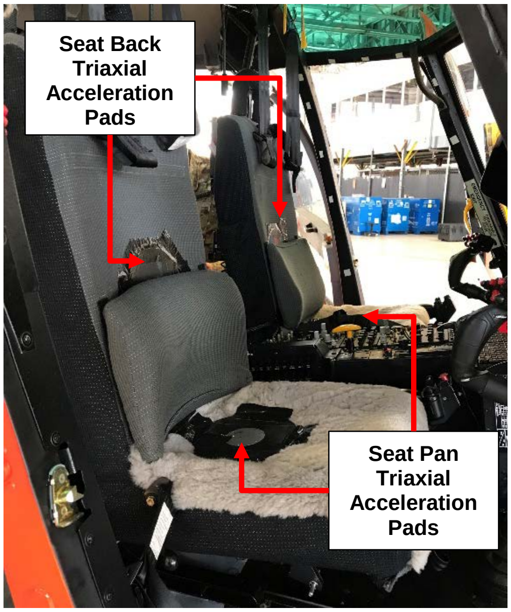

Figure 3. Acceleration Pads mounted to Seat Pan and Seat Back at Pilot/Copilot stations. Accelerometer Pack attached to lower left seat rail at both stations

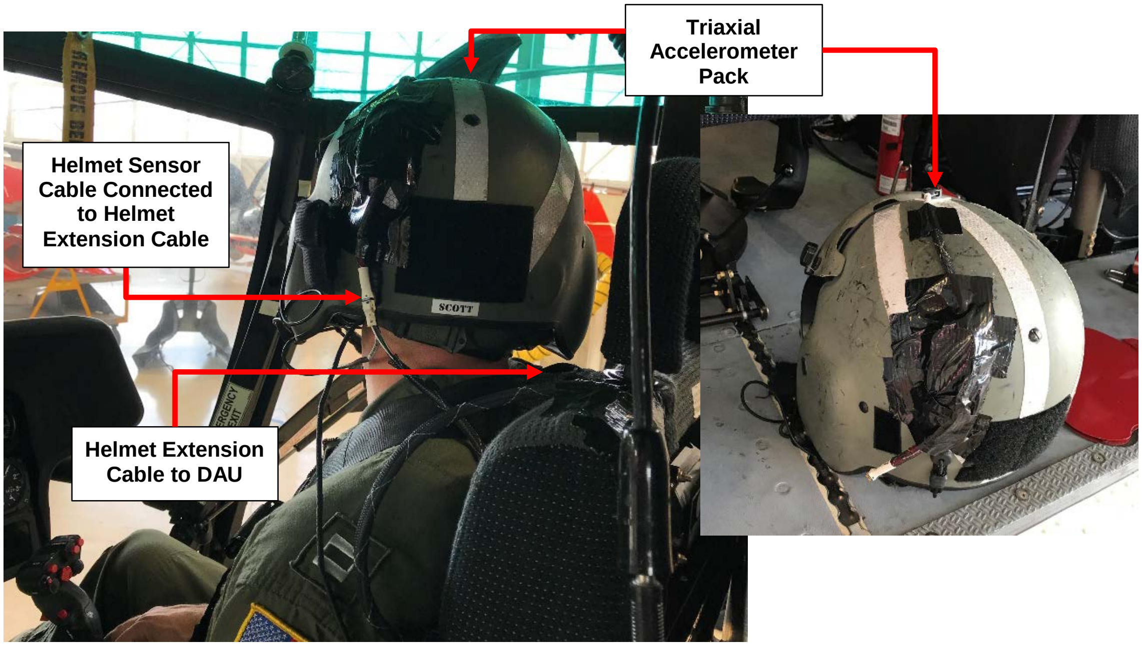

Figure 4. Acceleration Pack mounted to Pilot Helmet and attached to quick release helmet extension cable

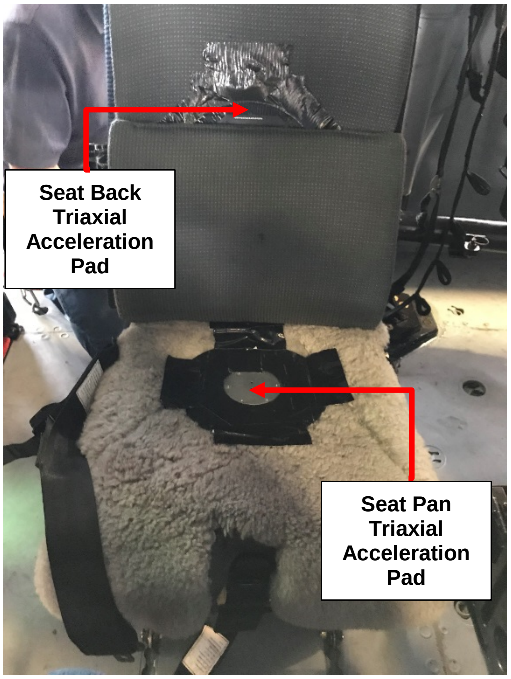

Figure 5. Acceleration Pads mounted to Seat Pan and Seat Back at Gunner station. Accelerometer Pack attached to cross bar at back of seat

A triggering device (Figure 1) was run from each DAU via cable to the swimmer station that was occupied by the test conductor, responsible for initiating data collection (see Section 3.3). Once triggered, the DAU would collect data for a pre-specified amount of time. Prior to flight, a laptop computer was used to conduct sensor balance, calibration checks, and arming of each DAU. The computer was used to assign a specific sensor associated with a measurement site and direction to a channel in the DAU. Once armed, the computer was disconnected from the DAU and stowed.

Triaxial acceleration pads were also mounted using double-sided adhesive tape to the seat pan and seat back of the gunner seat (Figure 5) and the swimmer seat (Figure 6). A triaxial accelerometer pack was mounted to the rigid cross bar located at the back of the gunner seat (not shown). A triaxial accelerometer pack was also mounted onto the floor next to the swimmer's seat (not shown). The swimmer's seat base was directly attached to the floor, although this is not easily seen in Figure 6.

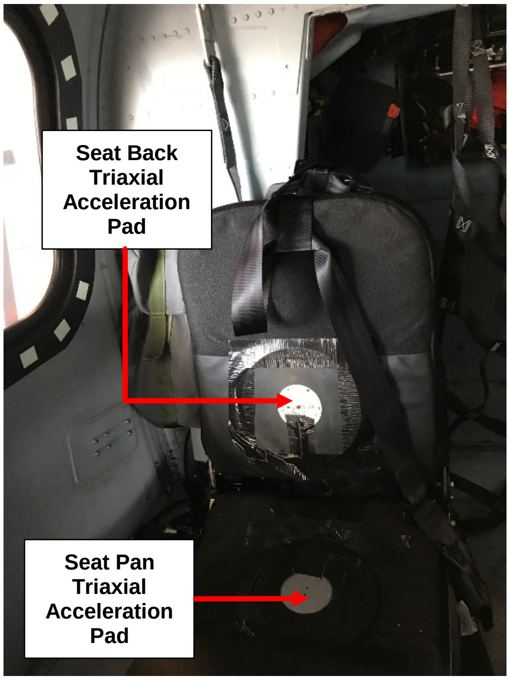

Figure 6. Acceleration Pads mounted to Seat Pan and Seat Back at Swimmer station. Accelerometer Pack attached to floor next to seat

3.3 Data Collection, Processing, and Analysis

3.3.1. Data Collection

Acceleration data were collected at the aircrew stations and measurement sites for the flight test conditions listed in Table A-2 MH-65D Flight Tasks and Flight Test Conditions Records. The flight test conditions were organized relative to flight tasks that were identified by the aircrew. The test conductor occupying the swimmer station was responsible for triggering all four DAUs once the pilot or copilot indicated that the aircraft was on the flight test condition. Multiple data records were collected for several of the conditions. Data records were collected throughout the flight and not necessarily collected in the order presented in Table A-2. The designated test conductor assured that the data records were numbered consecutively in the order they were collected.

Once triggered, data were automatically collected for 20 seconds, filtered at 250 Hz, and digitized at 1024 samples per second. Upon return of the aircraft, the laptop was reconnected to each DAU and the time histories for each channel downloaded to the computer for processing.

All data were collected during one flight test. Table A-2 lists the number of records collected for each flight test condition.

3.3.2. Data Processing and Analysis

A computer program developed by AFRL 711 HPW/RH was used to separate the 20-second records for each channel and assemble all channels for a particular record into a table of time histories. For each record, the time histories were processed using the MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) to estimate the constant bandwidth spectral content. Using Welch's Method (Welch, 1967), each 20-second time history was divided into two-second sub-segments with a 50% overlap. A Hamming window was applied to each sub-segment and the resultant power spectral densities averaged over the 20-second period. The root-mean-square (rms) acceleration, a_{rms}, was calculated from the power spectral densities in 0.5 Hz intervals. The constant bandwidth rms acceleration spectra were used to locate the peak accelerations.

Each acceleration time history was also processed in one-third octave proportional frequency bands using a software program developed for MATLAB® (Couvreur, 1997). The accelerations were reported at the center frequency of each respective one-third octave band. These data were used to assess the exposures in accordance with current standards.

The overall unweighted acceleration level, a_{uw}, between 1 and 80 Hz was calculated for each station at the floor or seat base, seat pan, seat back, and helmet (pilot only):

$$a_{uw} = \left[\sum_i a_{rmsi}^2\right]^{1/2} \qquad (1)$$

where a_{rmsi} is the rms acceleration associated with the *ith* frequency component (in 0.5 Hz increments for constant bandwidth analysis, and at the center frequency of the one-third octave band for proportional bandwidth analysis).

The assessment of discomfort (comfort reaction) and health risk followed the guidelines provided in ISO 2631-1 and the MIL-STD-1472G. The frequency weightings and multiplying factors listed in Table 2, based on human sensitivity to the location, frequency, and direction of vibration, were applied to the one-third octave band data for assessing comfort reaction and health risk. Figure 7 illustrates the frequency weightings W_d, W_k, and W_c.

Table 2. ISO 2631 Frequency Weightings and Multiplying Factors (ISO 2631-1: 1997)

	HEALTH RISK		COMFORT REACTION			
	Seat Pan		Seat Pan		Seat Back	
Direction	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor
X	W_d	$k = 1.4$	W_d	$k = 1.0$	W_c	$k = 0.8$
Y	W_d	$k = 1.4$	W_d	$k = 1.0$	W_d	$k = 0.5$
Z	W_k	$k = 1.0$	W_k	$k = 1.0$	W_d	$k = 0.4$

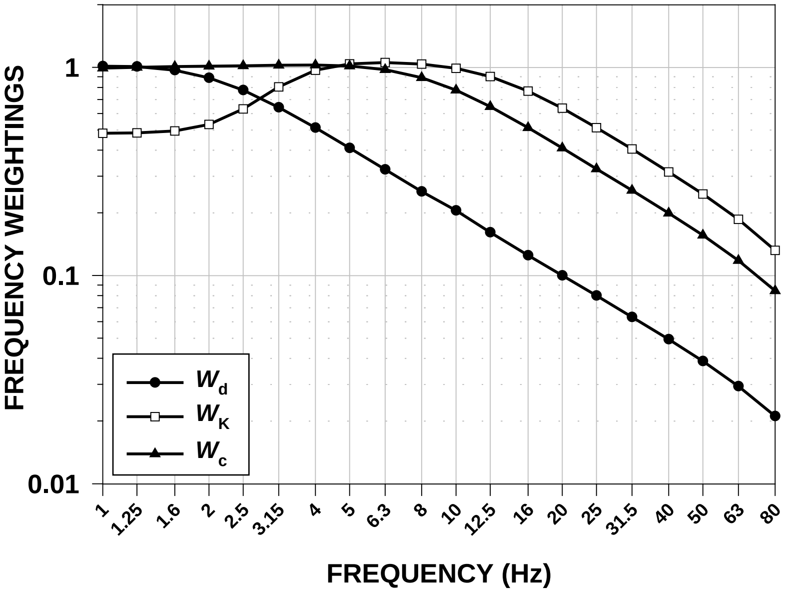

Figure 7. ISO 2631 Frequency Weightings W_d, W_k, and W_c (ISO 2631-1: 1997)

The overall weighted rms acceleration level, a_w, was calculated between 1 and 80 Hz in each axis (X, Y, and Z) relative to the coordinate system of the seated occupant using the one-third octave rms accelerations:

$$a_w = \left[k \sum W_{ji}^2 a_{rmsi}^2\right]^{1/2} \qquad (2)$$

where k represents the multiplying factor associated with a particular direction (X, Y, Z), measurement site (seat pan, seat back), and type of assessment (comfort, health); and W_{ji} is the frequency weighting associated with a particular direction and measurement site j, for the ith one-third octave center frequency component. For assessing comfort reaction, the *pVTV* was calculated at both the seat pan and seat back as the vector sum of the weighted fore-and-aft, lateral, and vertical accelerations, respectively, after applying the appropriate multiplying factors for the measurement site (seat pan or seat back):

$$pVTV = \left[k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right]^{1/2} \quad (3)$$

The *oVTV* was calculated as the vector sum of the seat pan and seat back *pVTVs*. The *oVTVs* were compared to the weighted accelerations associated with the comfort reactions given in ISO 2631-1: 1997, Annex C. The comfort reactions include “Not Uncomfortable”, “A Little Uncomfortable”, “Fairly Uncomfortable”, “Uncomfortable”, “Very Uncomfortable”, and “Extremely Uncomfortable”.

For assessing health risk, the highest weighted seat pan acceleration in any axis (fore-and-aft, lateral, or vertical) was used after applying the appropriate multiplying factors given in Table 2. The weighted data were compared to the ISO Health Guidance Caution Zones (HGCZs) (ISO 2631-1: 1997, Annex B). The ISO 2631-1: 1997 also states that the vector sum of the weighted accelerations at the seat pan (*pVTV*), after applying the appropriate multiplying factors for health risk, can be used when vibration in two or more axes are similar. For weighted accelerations falling below the lower boundary of the ISO HGCZs for the expected duration, health risks are unlikely. For those levels falling between the two boundaries, caution is given with respect to health risk, or there is a potential for health risk. For those levels falling above the upper boundary, health risks are likely for repeated occupational exposures. The current MIL-STD-1472G uses the guidelines of the ISO 2631-1; for exposures of 3.5 hours and below, the lower boundary of the HGCZs follows the more conservative fourth power relationship described in the ISO Annex B. Figure 8 illustrates the ISO HGCZs and includes the lower boundary defined in the MIL-STD for exposures of 3.5 hours and below. The current MIL-STD-1472G states the following:

> *“For exposures lasting 8.0 hours or less, the seat pan frequency weighted triaxial RMS accelerations in any orthogonal direction for any occupied space shall not fall within the zone labeled “Health Risks are LIKELY”. Preferably the weighted accelerations shall fall within the “Minimal Risk to Health” zone. For exposures lasting greater than 8.0 hours, the seat pan frequency weighted triaxial RMS accelerations shall not exceed 0.315 m/s^2. If the weighted accelerations fall within the “Caution Zone”, a warning to occupants shall be provided indicating the potential health risk”*

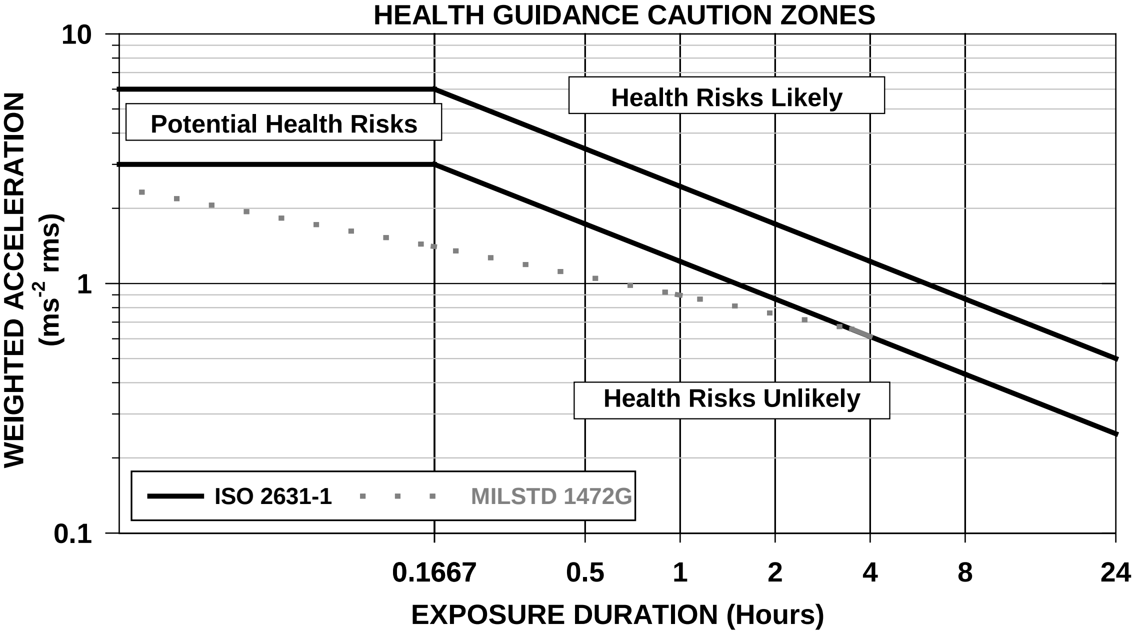

Figure 8. ISO 2631-1 Health Guidance Caution Zones (HGCZs)
Plot includes more conservative lower boundary defined in MIL STD 1472G for exposures at 3.5 hours and below

A revision of the MIL-STD-1472 (version H) is in progress that may include modifications to the exposure criteria.

4.0 RESULTS

All Figures and Tables referred to in this section are located in the Appendix. A total of 160 records were collected for the flight test conditions listed in Table A-2 at the pilot, copilot, and gunner stations. The large DAU located at the swimmer (test conductor) station (Table A-1) was limited to 153 20-second records. At this station, data are not available for Opposing Heading (4 records), Landing (No Hover) (1 record), and Landing (Running) (2 records).

4.1 Characteristics of the Multi-Axis Accelerations Aboard the MH-65D

4.1.1. MH-65D Acceleration Spectra

It was expected that a peak in the acceleration spectra would occur in the vicinity of the main rotor speed of the aircraft. The frequency associated with the rotor speed is referred to as the propeller rotation frequency or PRF in this document. The highest peak typically occurs at the blade passage frequency or BPF, which is predicted as the number of blades multiplied by the PRF. Both the PRF and BPF may vary slightly depending on the flight maneuver and whether the aircraft is operated at 100% power. Additional peaks were also expected at multiples of the BPF. The direction of the highest acceleration associated with the BPF was unknown prior to the analysis of these data.

Figures A-1 through A-4 illustrate the acceleration spectra for a selected data record collected at each station, measurement site, and direction during level flight at 100 KIAS. As expected, the highest peak tended to occur at what was presumed to be the BPF. The peak consistently occurred at approximately 23.5 Hz. The figures also show that the peak associated with the BPF occurred in all three directions at various magnitudes, depending on the station. Small peaks were also observed at multiples of the BPF. Based on these observations, it was estimated that the PRF for level flight occurred at approximately 5.9 Hz. A relatively small peak of varying magnitude was observed in the figures near 6 Hz. The peak appeared to be the highest in the vertical (Z) direction. At the pilot helmet, the vertical peak at 6 Hz tended to be more substantial and, in several cases, higher than the vertical peak associated with the BPF. Pilot helmet vibration was quite damped at frequencies beyond the BPF.

4.1.2. Overall Unweighted Accelerations

Figures A-5 through A-8 illustrate the mean unweighted overall accelerations ± one standard deviation at the pilot, copilot, gunner, and swimmer stations, respectively, at the seat base or floor, seat pan, and seat back measurement sites, for each flight test condition. Tables A-3 through A-6 include the unweighted overall seat pan accelerations for each level flight record at each of the four aircrew stations. The Repeated Measures Analysis of Variance and Bonferroni Comparison Test were applied to evaluate the significance of direction on the overall unweighted accelerations at the three measurement sites for level flight. Significant differences were associated for $P<0.05$.

In general, all stations showed overall accelerations for level flight that were similar to or higher than the overall accelerations observed for the other flight test conditions. At the pilot station, located on the right side of the aircraft, the overall unweighted vertical (Z) accelerations at the seat base were significantly higher than the overall horizontal (X and Y) accelerations at all four airspeeds (Figure A-5, Table A-7). Figure A-5 also shows that the vertical (Z) accelerations at the seat base tended to decrease with increasing airspeed. Although not statistically evaluated, higher overall vertical (Z) accelerations were also observed at the seat base for most of the other flight test conditions. In contrast, Figure A-5 shows that, at the pilot seat pan, the overall unweighted accelerations tended to be similar in all three directions, with mixed statistical findings (Table A-7). These trends were also observed for the other flight test conditions. The directional effects at the pilot seat back were similar to the trends observed at the seat base; significantly higher overall unweighted accelerations occurring in the vertical (Z) direction for level flight with decreases in the overall levels with increasing airspeed (Figure A-5, Table A-7). Again, the higher vertical (Z) levels were observed for most of the other flight test conditions.

At the copilot station, located on the left side of the aircraft, the overall unweighted seat base vertical (Z) accelerations at all airspeeds, except 140 KIAS, were significantly higher than the overall unweighted horizontal (X and Y) accelerations (Figure A-6, Table A-7). At 140 KIAS, the overall levels in the lateral (Y) direction were statistically higher as compared to the vertical (Z) and fore-and-aft (X) directions, although Figure A-6 shows that any differences were small, compared to the differences at the lower airspeeds. As with the pilot station, the vertical (Z) accelerations at the copilot seat base tended to decrease with increasing airspeed, and the vertical (Z) levels also tended to be the highest for most of the other flight test conditions. At the copilot seat pan, the overall levels in the lateral (Y) direction were significantly higher as compared to the other directions at all airspeeds. This tendency at the seat pan was also observed for many of the other flight test conditions. At the copilot seat back, the results were similar to those observed at the seat pan and in contrast to the directional effects observed at the pilot station; significantly higher overall seat back accelerations in the lateral (Y) direction. The overall seat back accelerations in both the lateral (Y) and vertical (Z) directions were statistically higher compared to the levels in the fore-and-aft (X) direction. In addition, the overall copilot seat back levels in the fore-and-aft (X) direction tended to be the lowest for the other flight test conditions (Figure A-6).

At the gunner station, located mid cabin towards the left side of the aircraft, both the seat base and seat back showed statistically higher overall vertical (Z) accelerations at all four airspeeds that tended to decrease with increasing airspeed (Figure A-7, Table A-7), with higher vertical (Z) overall accelerations also tending to occur for the other flight test conditions. These results are similar to the findings at the pilot station located on the right side. In contrast, at the gunner seat pan, the fore-and-aft (X) overall accelerations were significantly higher. This trend was also observed at many of the other flight test conditions.

At the swimmer station, located in the aft cabin right side, the floor and seat back showed statistically higher overall unweighted accelerations in the vertical (Z) direction at all airspeeds (Table A-7). However, the trend for decreasing levels with increasing airspeed was not observed (Figure A-8). The overall lateral (Y) accelerations were the lowest at the floor, while the overall fore-and-aft (X) accelerations were the lowest at the seat back (Figure A-8, Table A-7). At the swimmer seat pan, the overall vertical (Z) accelerations were statistically higher at all airspeeds except 80 KIAS. At 80 KIAS, the overall fore-and-aft (X) accelerations were statistically higher (Table A-7), but appeared similar to the vertical (Z) levels (Figure A-8). The overall lateral (Y) seat pan accelerations were statistically the lowest at all airspeeds.

It is interesting to note that the overall unweighted vertical (Z) seat base or floor accelerations at 120 KIAS with the gear down were either similar to or slightly less than the overall vertical (Z) levels at 120 KIAS without the gear down. In addition, it was not clear that turning off the automatic flight control system (AFCS) had any effect on the vibration levels at the seat base or floor.

4.2 Assessment of the MH-65D Aircrew Comfort and Health Risks

4.2.1. Overall Weighted Accelerations

It is cautioned that the summary provided below on the weighted overall accelerations are observations and have not been statistically evaluated for significant effects of measurement site and direction.

Summary plots of the mean overall unweighted accelerations at the seat base or floor, seat pan, and seat back, and the mean overall weighted accelerations at the seat pan and seat back for level flight are provided in Figure A-13 for comparison. The figure also includes plots of the *pVTV*s and *oVTV* for the comfort assessment, and the *pVTV*s for the health assessment using the level flight data. The figure shows that the highest unweighted overall accelerations at the seat pan did not necessarily occur in the Z direction, as was described in section 4.1.2 for the pilot, copilot, and gunner stations. However, the highest weighted overall accelerations at the seat pan were notably in the Z direction at all stations, even with the 1.4 multiplying factor applied to the horizontal directions in accordance with Table 2 for assessing health risk. Figure 7 also shows that the frequency weighting, W_d, for the horizontal directions reduces the contributing accelerations to a much greater extent than in the vertical direction (W_k), particularly in the vicinity of the blade passage frequency (~23.5 Hz). Figure A-13 shows that the highest unweighted overall accelerations at the seat back occurred in the lateral (Y) or vertical (Z) direction depending on the station, as described in section 4.1.2, while the highest weighted overall accelerations tended to occur in the X direction. The frequency weightings and multiplying factors may have contributed to the seat back observations (Table 2, Figure 7).

4.2.2. Aircrew Vibration Comfort Assessment (ISO 2631-1 Comfort Reactions)

The guidelines in ISO 2631-1 were used to assess the comfort reactions of the aircrew. At all stations, the assessment was based on the *oVTV* calculated as the vector sum of the *pVTVs* estimated at the seat pan and seat back in accordance with Equation 3 and using the frequency weightings and multiplying factors in Table 2. The Comfort Reactions are independent of time.

Figures A-9 through A-12 plot the *oVTV*s for assessing comfort reaction for all flight test conditions at four stations All figures include illustration of the ISO 2631-1 Comfort Reactions. Figure A-9 shows that, based on the *oVTV*s calculated at the pilot station, the vibration associated with en route flight operations was primarily considered “fairly uncomfortable”. The other tasks and associated flight test conditions generated vibration that was considered “not uncomfortable” and “a little uncomfortable”. The one exception of interest was the *oVTV*s calculated during approach to target of interest (TOI), where all records indicated a comfort reaction of “uncomfortable”. Figure A-10 shows that, based on the *oVTV*s calculated at the copilot station, the vibration associated with flight operations was primarily considered “a little uncomfortable", with some exceptions (notably during climb and level flight at 140 KIAS). Figure A-11 shows that, based on the *oVTV*s calculated at the gunner station, the vibration associated with flight operations was "fairly uncomfortable" and, in some cases, "uncomfortable", with one record associated with level flight at 80 KIAS being considered "very uncomfortable". It was speculated that the large variations in the *oVTV*s for level flight at 80 KIAS may have been influenced by the occupant shifting or changing posture during data collection. Figure A-12 shows that, based on the *oVTV*s calculated at the swimmer station, the vibration associated with flight operations was "fairly uncomfortable", with all records at 140 KIAS being "uncomfortable". In summary, the least discomfort from vibration, based on the ISO comfort reactions, occurred at the copilot station located on the left side of the cockpit.

With reference to Figure A-13, the level flight *oVTV*s calculated at the four stations were very similar to the seat pan *pVTV*s for assessing comfort reaction. As noted in the figure, the level flight *pVTV*s calculated at the seat back were relatively small. This strongly suggests that the seat back contribution to the comfort reaction was minimal during level flight.

4.2.3. Aircrew Vibration Health Risk Assessment (ISO 2631-1)

The guidelines in the ISO 2631-1 were also used to assess health risk, using the level flight seat pan data. It was assumed that the aircrew would spend most of the daily mission in level flight. When assessing the potential for health risk, the lower boundary of the ISO 2631-1 HGCZs was used and not the more conservative MIL-STD-1472G boundary for exposures less than 3.5 hours (see Figure 8). The health risk assessment is dependent on the daily exposure duration. It was assumed that the range of accelerations collected during level flight were representative of the expected acceleration levels occurring for various missions. This is based on the assumption of no adverse weather (such as high wind) or evasive maneuvering (such as may occur when under live fire).

Tables A-3 through A-6 include the weighted overall seat pan accelerations and seat pan *pVTV*s for assessing health risk for each level flight record at each of the four stations. The tables also list the minimum exposure duration for each listed record, in hours, associated with potential health risk (lower boundary of HGCZs) and likely health risk (upper boundary of HGCZs) (Figure 8 (ISO 2631-1 boundaries only)). These exposure durations were based on the highest overall seat pan acceleration occurring in any direction, as well as the seat pan *pVTV* for health risk. The highest weighted acceleration at the seat pan always occurred in the vertical (Z) direction for all stations, as observed in Figure A-13 and Tables A-3 through A-6. Any exposure duration below the lower boundary would be associated with minimal health risk. Any exposure duration between the lower and upper boundaries would be associated with the potential for health risk, and any exposure at or above the upper boundary would be associated with a likely health risk. The durations were calculated based on the square root time dependency. The durations and associated acceleration levels are color-coded (orange for lower boundary and red for upper boundary) to easily identify which airspeeds and records would reach the two boundaries in less than 8 hours. In general, Figure 13 and the tables show that the overall weighted seat pan accelerations in the vertical (Z) direction were only slightly less than the seat pan *pVTV*s, indicating very little contribution from the horizontal seat pan accelerations.

Figure A-14 illustrates the minimum exposure durations associated with the potential for health risk at all four stations at each airspeed based on the seat pan *pVTV*s. Figure A-15 illustrates the minimum exposure durations associated with likely health risk. Both figures include the minimum exposures at 120 KIAS with the gear down. The figures indicate that, with the exception of the gunner station, the lowest exposure durations occurred at the highest airspeed of 140 KIAS. With the exception of level flight with the gear down, both the copilot and swimmer stations showed decreases in exposure durations with increasing airspeed. Increasing durations were associated with higher seat pan *pVTV*s. In general, the level flight vibration at the pilot, gunner, and swimmer stations was associated with a minimum exposure duration for potential health risk in less than 8 hours (Figure 14 and Tables A-3, A-5, and A-6). At the copilot station, this trend was primarily observed at the two higher airspeeds (120 and 140 KIAS) (Figure 14 and Table A-4). Several records at the gunner station for level flight at 80 KIAS, and all records at the swimmer station for level flight at 140 KIAS, showed that the occupants would reach the minimum duration for likely health risk in less than 8 hours (Figure 15 and Tables A-5 and A-6). Interestingly, both the copilot and gunner stations showed relatively higher exposure durations and, therefore, lower weighted accelerations and *pVTV*s, at 120 KIAS with the gear down as compared to 120 KIAS with the gear stowed (Figures A-14 and A-15). The durations and associated weighted acceleration levels were similar with the gear down and gear stowed at the pilot and swimmer stations (Figures A-14 and A-15).

The following is a more detailed synopsis of the level flight exposure effects on health risk at each station. Level flight with the gear down is not considered in the synopsis.

Figure A-14 and Table A-3 show that the pilot was exposed to potential health risk for daily flight durations between 4 and 7 hours at airspeeds ranging from 80 to 120 KIAS, and exposed to potential health risk between 3 and 4 hours at the highest airspeed (140 KIAS). This was true regardless of whether the overall weighted seat pan Z accelerations or the seat pan *pVTV*s were used for the assessment (Table A-3). Figure A-15 and Table A-3 also show that the pilot would be exposed to likely health risk for daily exposures that, at a minimum, lasted less than about 12 hours (based on *pVTV*s).

Figure A-14 and Table A-4 show that the copilot was exposed to potential health risk for daily flight durations lasting 8 hours or longer at the lower airspeeds of 80 and 100 KIAS (Table A-4 shows two possible exceptions at 100 KIAS). The copilot was exposed to potential health risk between about 5 and 7 hours at 120 KIAS, and exposed to potential health risk between 3 and 4 hours at the highest airspeed (140 KIAS, based on *pVTV*s). The copilot would not be exposed to likely health risks for daily flights lasting, at a minimum, less than about 15 hours (Table A-4, based on *pVTV*s).

Figure A-14 and Table A-5 show that the gunner was exposed to potential health risk for daily flight durations lasting between 3 and 6 hours, regardless of airspeed. It was not clear what caused the large variation in the exposure durations at 80 KIAS that showed potential health risk in less than two hours for several records, and in less than one hour for one record (Table A-5). It was speculated that the results were influenced by occupant shifting or changing posture during data collection, as was also speculated for the comfort assessment. In contrast to the other stations, the gunner exposures at the highest airspeed of 140 KIAS did not necessarily result in the lowest daily flight duration.

Figure A-14 and Table A-6 show that the swimmer was exposed to the potential for health risk for daily flight durations lasting between 4 and 6 hours at 80 and 100 KIAS, between 2 and 3 hours at 120 KIAS, and in less than 2 hours of flight at 140 KIAS. At the swimmer station, health risks are likely for daily flight durations lasting about 7 hours at the highest airspeed (140 KIAS).

5.0 DISCUSSION AND CONCLUSIONS

This document provides the characterization and assessment of aircrew vibration exposure onboard the MH-65D Dolphin. Included is a synopsis of the seat base or floor, seat pan, and seat back acceleration spectra during various flight operations or flight tasks, and specific flight conditions. The characteristics of the spectra generated by the MH-60D were similar to that observed during other investigations conducted on rotary-wing and tilt-rotor aircraft, where the highest accelerations were transmitted to the seated aircrew at distinct frequencies associated with the propulsion system (Smith, 2005; Smith, & Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008; Smith, Chervak, & Steinhauer, 2014; Smith, Chervak, & Clasing, 2019). The vibration associated with the propeller rotation frequency or PRF was typically quite low in magnitude for these aircraft and occurred below 10 Hz. During flight aboard the MH-60D, a small peak associated with the PRF was quite distinct around 6 Hz but of relatively low magnitude at the seat base/floor, seat pan, and seat back. However, the low frequency peak was more prevalent at the pilot helmet and appeared to be the highest in the vertical direction. As mentioned, depending on the flight condition, the peak associated with the PRF at the helmet was observed to be higher as compared to the peak associated with the BPF at the helmet. This is not surprising since the peak around 6 Hz is in the vicinity of whole-body resonance and is typically amplified at the head, while higher frequency vibration is quite damped unless the head or helmet is in contact with the seat back or a head rest. It is not clear whether this low frequency vibration at the helmet could affect comfort or health risk, since the assessment of head (or helmet) vibration is not addressed in the current vibration exposure standards and guidelines. It is known that low frequency vibration of the head and helmet can influence visual performance, especially when using helmet-mounted optical devices. A further analysis of the head/helmet motions is required to address performance issues. At the seat base/floor and seat/occupant interfaces, the highest vibration tended to occur at the blade passage frequency or BPF in the vicinity of 23.5 Hz for all flight test conditions, at all stations, with additional peaks observed primarily as harmonics of the BPF. Peak magnitudes were observed in the fore-and-aft (X), lateral (Y), and vertical (Z) directions, depending on the flight condition, station, and measurement site.

As shown in Figure A-13, the higher frequencies generated by the MH-65D, as with other rotary-wing/tilt-rotor aircraft, can be highly weighted once the ISO 2631-1 frequency weightings and multiplying factors are applied for calculating the overall weighted accelerations, *pVTV*s, and *oVTV*s. This can dramatically reduce the contribution of the vibration to the comfort reaction and health risk assessments defined in the standards. Regardless, the majority of flight test conditions were associated with a comfort reaction of “fairly uncomfortable”. The one exception occurred at the copilot station located on the left side of the aircraft. The comfort reactions associated with this station were the lowest observed among the aircrew stations. The largest variations in comfort reaction occurred at the gunner station and swimmer station, both located in the cabin area. As mentioned, the swimmer seat was attached directly to the floor in the aft cabin section. In accordance with the ISO 2631-1 guidelines, the level flight exposures were associated with the potential for health risk, and even likely health risk, to the aircrew in less than 8 hours of daily or occupational flight operations, as illustrated in Figures A-14 and A-15.

Figure 9 summarizes the mean minimum daily exposure durations ± one standard deviation among the three level flight airspeeds (excluding the gear down data) associated with the ISO 2631-1 potential for health risk and health risks likely (lower and upper boundary of the Health Guidance Caution Zones shown in Figure 8, respectively). The summary includes the pilot, copilot, gunner, and swimmer stations. These stations included all level flight records measured during the study and were representative of the vibration levels expected during various flight task operations associated with the MH-65D. Relative to one standard deviation, the figure shows that the vibration exposures at all stations, with a few exceptions for the copilot, were associated with the potential for health risk in less than 8 hour of daily flight. Relative to the mean values, the gunner and swimmer daily exposures were restricted to flight durations lasting less than about 4 hour and 3.4 hours, respectively. As also noted in the figure, the mean minimum daily durations associated with likely health risk were approximately four times the mean minimum daily durations associated with potential health risk. Based on the mean values and one standard deviation, all stations would require daily flights consistently greater than 8 hours to be considered a likely health risk. The swimmer station was one possible exception, especially if operations included higher airspeeds around 140 KIAS where health risk was likely in approximately 7 hours of flight (Table A-6).

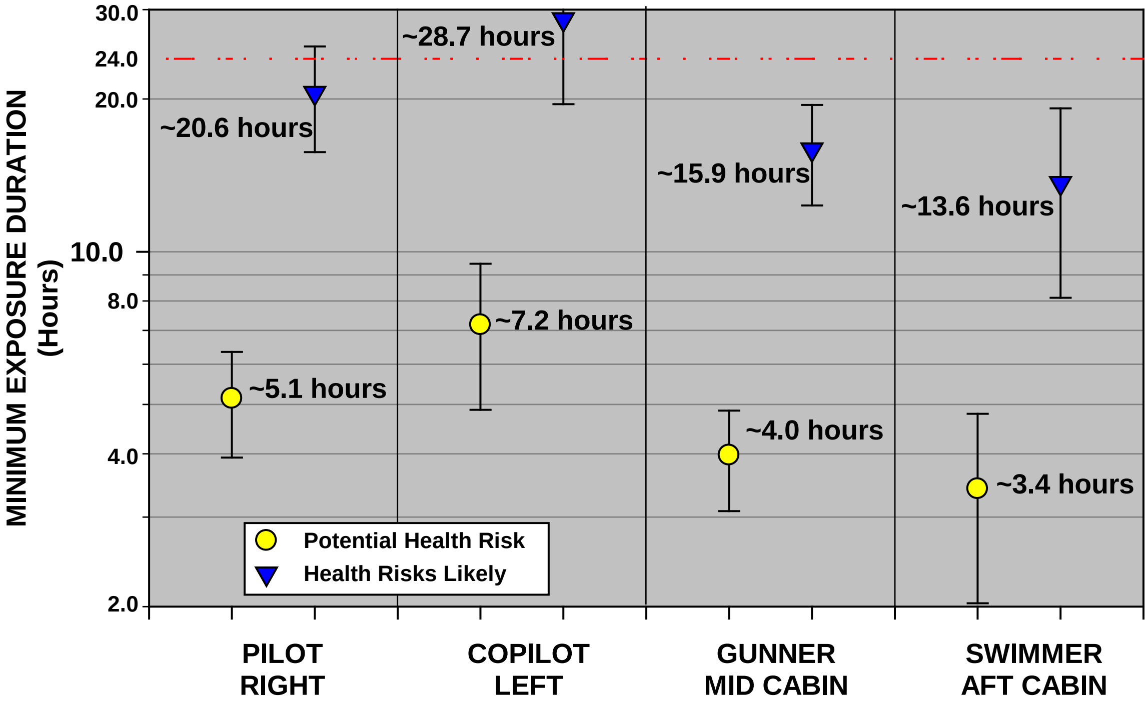

Figure 9. Mean Minimum MH-65D Daily Exposure Durations ± One Standard Deviation for Potential Health Risk and Health Risks Likely (ISO 2631-1)

Figure 10 compares the seat pan *pVTV*s, associated with level flight at various operationally relevant airspeeds, from other aircraft that have been previously assessed for health risk in accordance with ISO 2631-1. The figure includes bands of daily exposure durations associated with potential health risk. All of the tested aircraft, including the MH-65D, expose the aircrew to potential health risk for daily flight durations lasting less than 8 hours.

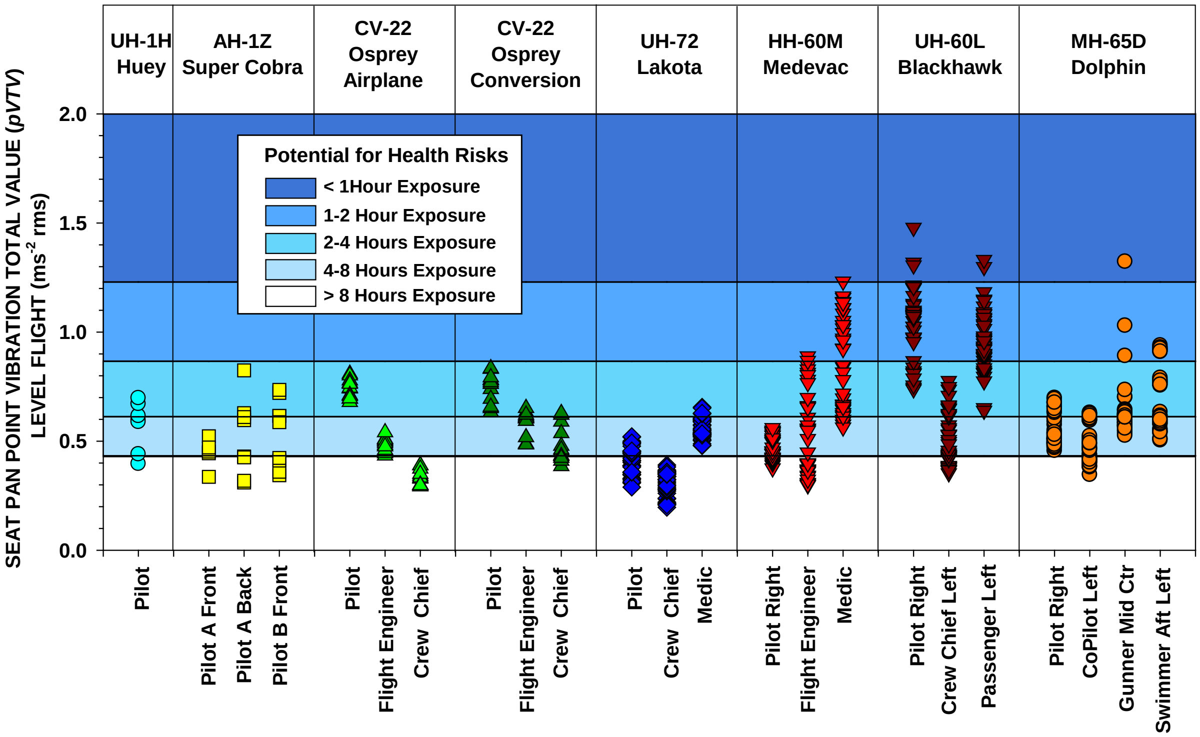

Figure 10. Comparison of Health Risk *pVTVs* Among Rotary-Wing/Tilt -Rotor Aircraft

The assessment guidelines provided in the standards are based on human physical and psychophysical (perceptional) responses to the frequency, magnitude, and direction of the vibration exposure. These response characteristics are expressed by the frequency weightings and multiplying factors that are applied during the assessment process. Humans are the most sensitive to vibration occurring below 10 Hz, particularly in the vertical (Z) direction. Vibration at these lower frequencies can produce relative motions between body regions (vertical motion) and cause postural instabilities (when combined with low frequency horizontal motion) that are readily perceived as being uncomfortable and even painful. Whole-body resonance has been identified during vertical vibration in the range of 4 and 8 Hz, where the large relative motions between the upper and lower torso transmit easily to the head. As described above, low frequency, primarily vertical peaks were observed and amplified at the helmet, although the consequences of the motions are unknown without further investigation. The comfort reactions defined in ISO 2631-1 Appendix C are based on passenger expectations in public transportation, where exposures are expected to occur at lower frequencies and shorter durations than in military operations. Caution should be taken when applying these reactions to military environments, where longer durations and higher frequency exposures could affect aircrew perception. Likewise, the ISO 2631-1 health risk of vibration has primarily been associated with the lumbar spine and connected nervous system. It is logical to conclude that higher magnitude, lower frequency vibration could contribute to these symptoms due to the relative upper and lower torso motions and postural instability that can dynamically and repeatedly stress the spinal column and transmit motions to the head. Vibration transmission to the upper torso and head dramatically decreases at frequencies beyond 10 Hz as observed in this study and previous studies, unless there are substantial amplitudes or the upper torso/head is in direct contact with a vibrating surface, as mentioned above. Humans primarily perceive higher frequency vibration at the interfaces where the body is in contact with the vibrating surface. It is known that higher levels of higher frequency vibration can cause tonic muscle reflex but research that associates this physiological response to possible muscle fatigue and even tissue damage during repeated exposures is extremely limited if nonexistent. This suggests there could be a substantial impact on defining the most appropriate criteria to apply for assessing discomfort and health risk in military air vehicles.

In summary, the results of the assessments on the MH-65D Dolphin further support the substantial influence of operational vibration on the discomfort and pain that has been associated with the operation of these aircraft, particularly given the magnitudes of the higher frequency exposures that still result in a potential health risk according to the standards and guidelines. The higher frequency characteristics of the vibration do warrant investigation of the mechanisms by which the vibration can cause pain and injury and, once understood, lead to the development of more robust discomfort and pain mitigation strategies.

6.0 RECOMMENDATIONS

1. Conduct periodic monitoring of the aircrew by occupational health specialists, particularly documenting reports of discomfort, pain, tingling, and numbness in the back, buttocks, and lower extremities. This could be accomplished using the aircrew surveys developed for this study or some modification. (The results of the survey conducted under this study will be documented in a subsequent report.)

2. Add seat pan and seat back cushion support that can improve posture and also mitigate some of the higher frequency vibration entering the occupant at interfaces, particularly for aircrew occupying the back of the aircraft. Attention should be paid to the multi-axis characteristics of the exposures.

3. Consider the use of passive, semi-active, and active vibration mitigation technologies either added to the existing seats or via new seat design concepts. The data collected during this project on four different rotary-wing platforms, as well as the data from past studies on rotary-wing/tilt-rotor aircraft (Figure 10), should be leveraged in the development of appropriate equipment design criteria and equipment concept testing strategies for improving the safety and health of military aircrew.

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APPENDIX: RESULTS – FIGURES AND TABLES

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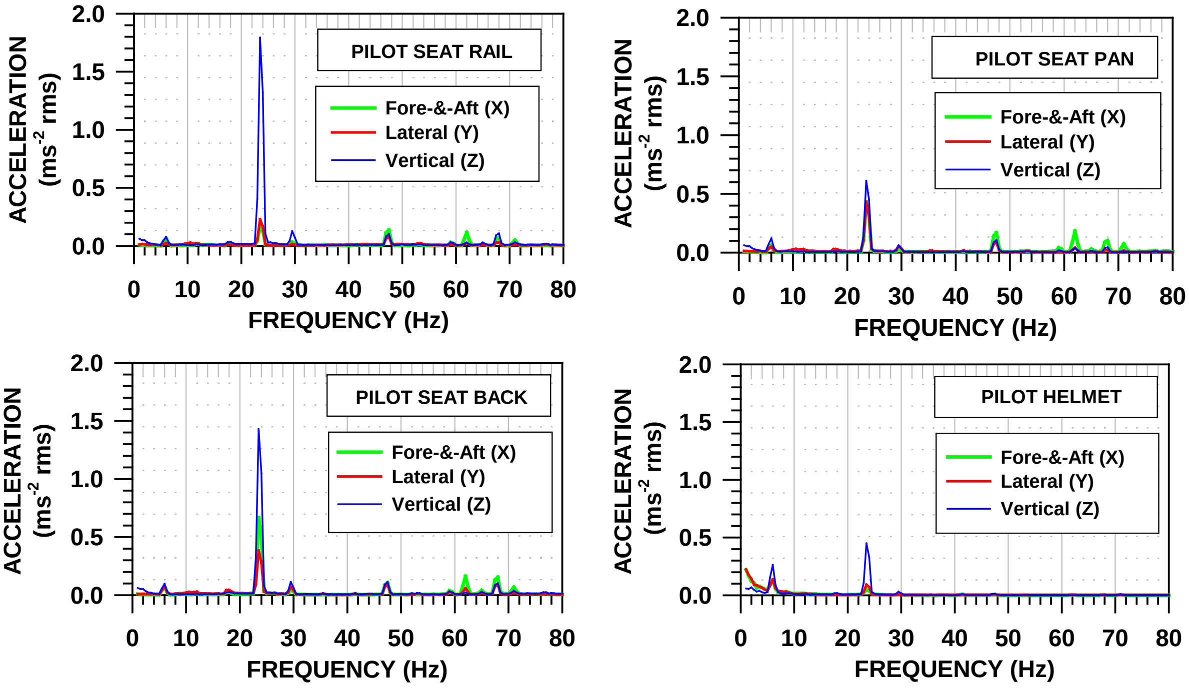


Figure A-1. Sample Acceleration Spectra at Level Flight 100 KIAS at the Pilot Station

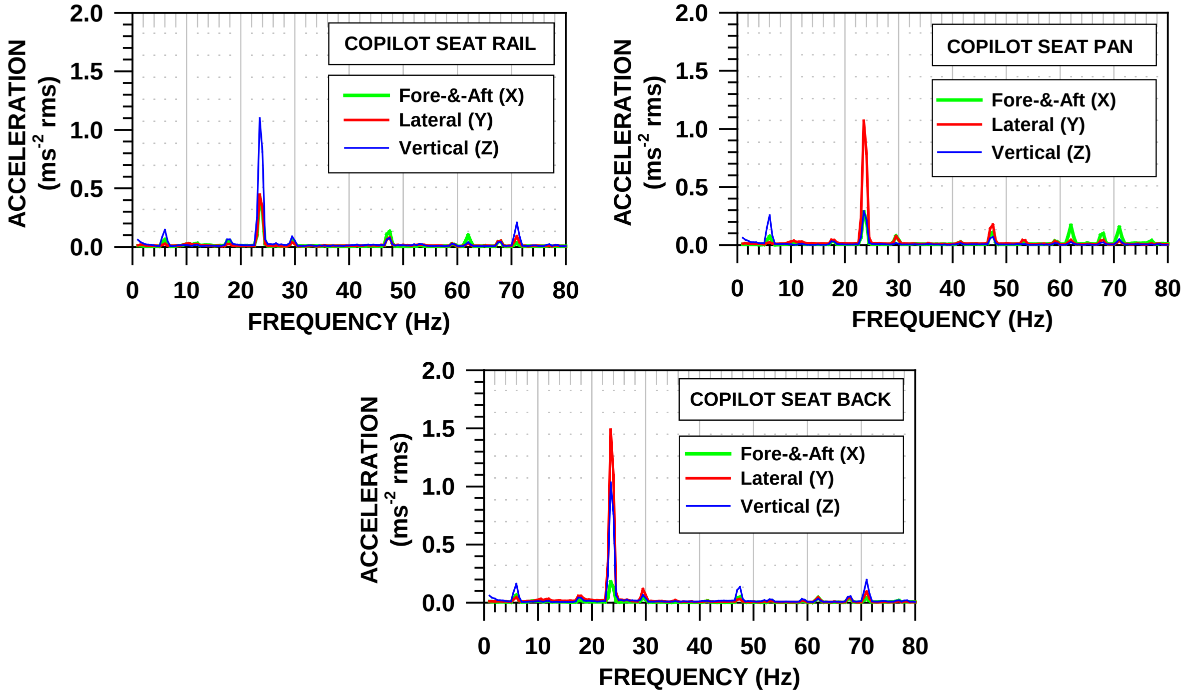


Figure A-2. Sample Acceleration Spectra at Level Flight 100 KIAS at the Copilot Station

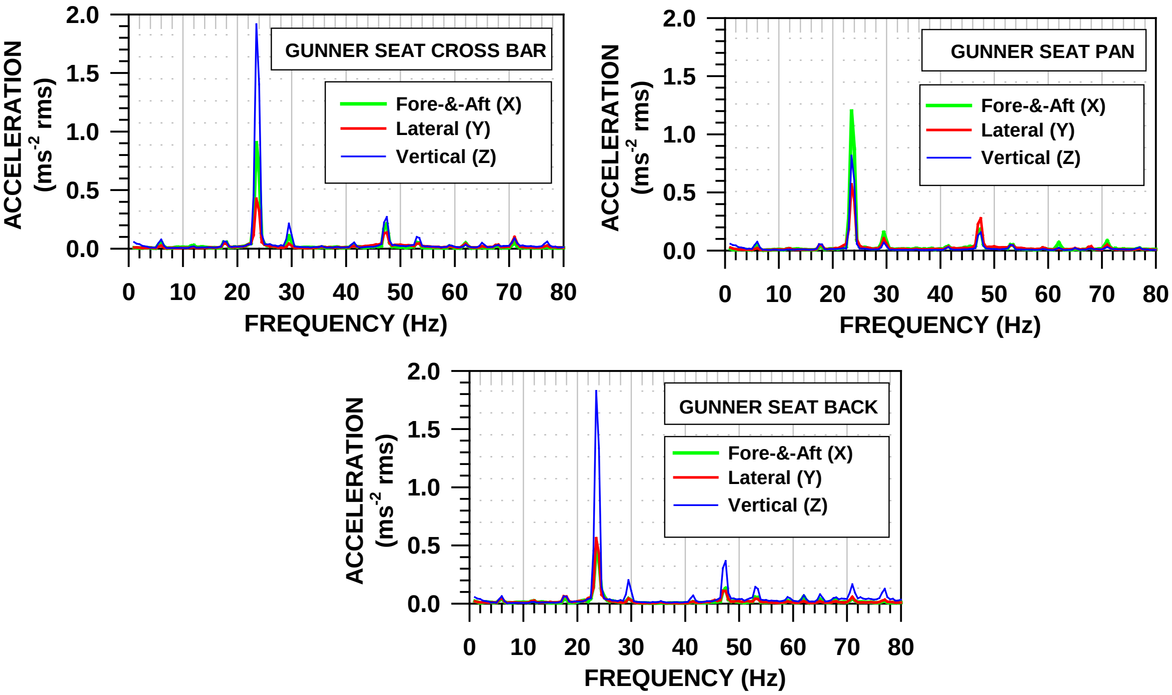


Figure A-3. Sample Acceleration Spectra at Level Flight 100 KIAS at the Gunner Station

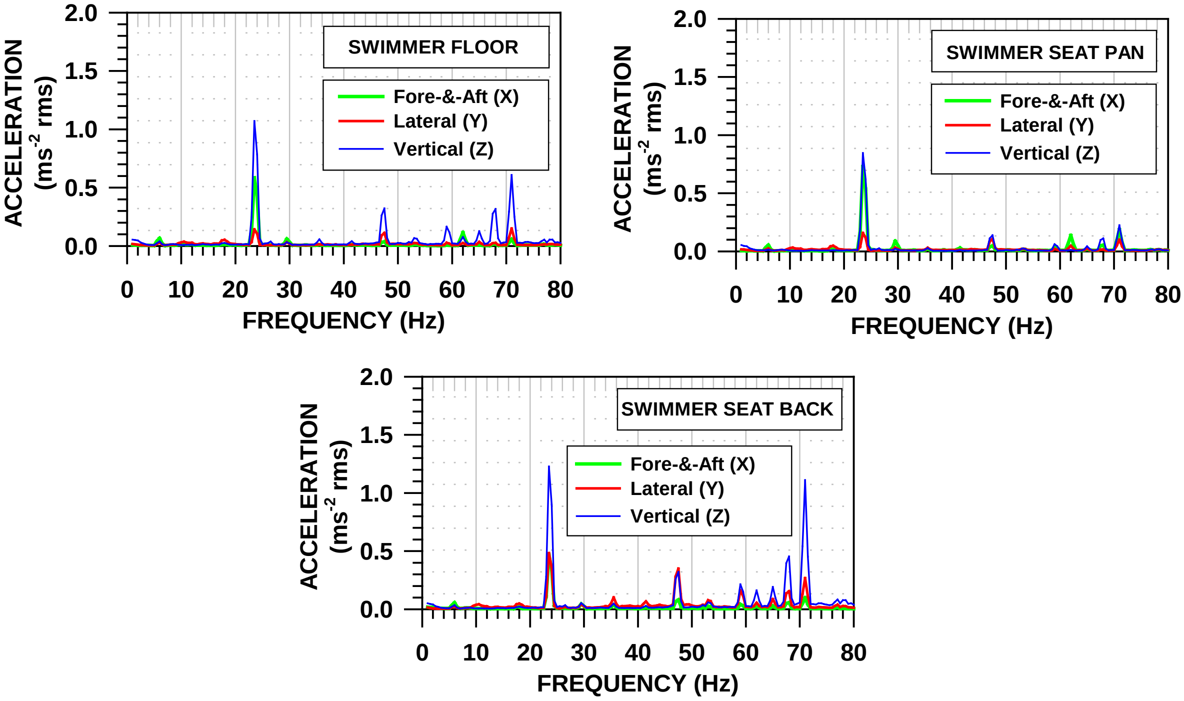


Figure A-4. Sample Acceleration Spectra at Level Flight 100 KIAS at the Swimmer Station

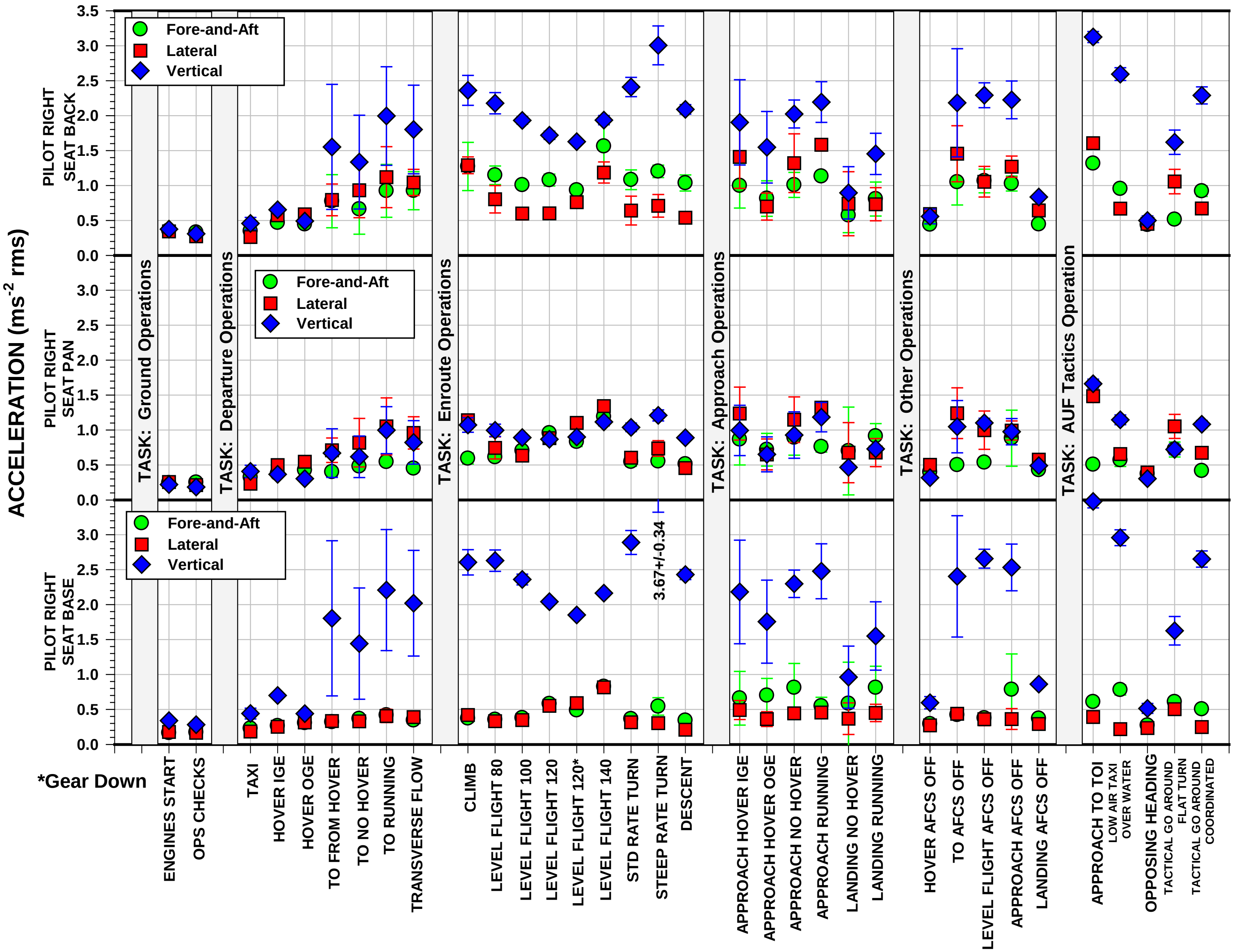


Figure A-5. Pilot Mean Overall Unweighted Accelerations ± One Standard Deviation

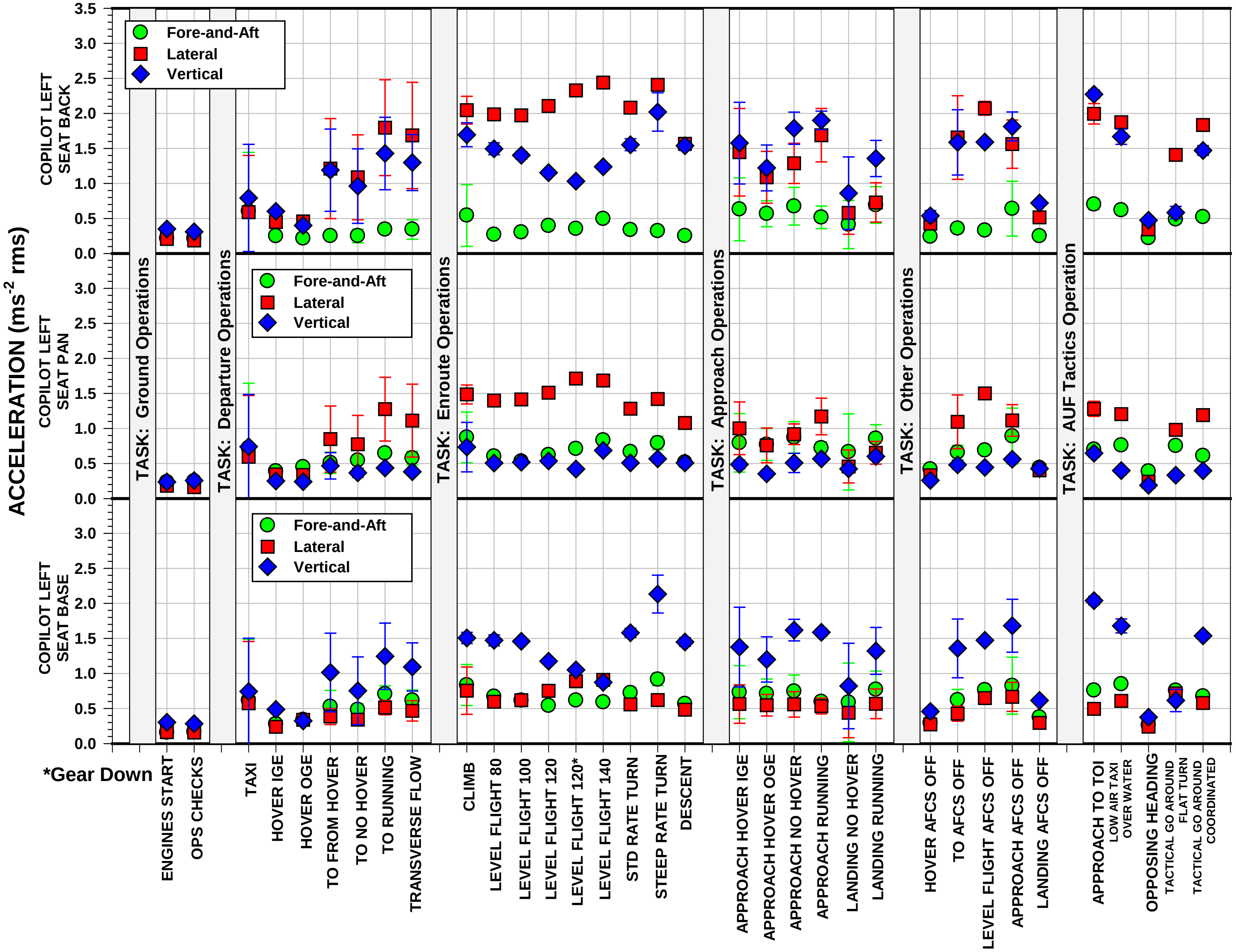


Figure A-6. Copilot Mean Overall Unweighted Accelerations ± One Standard Deviation

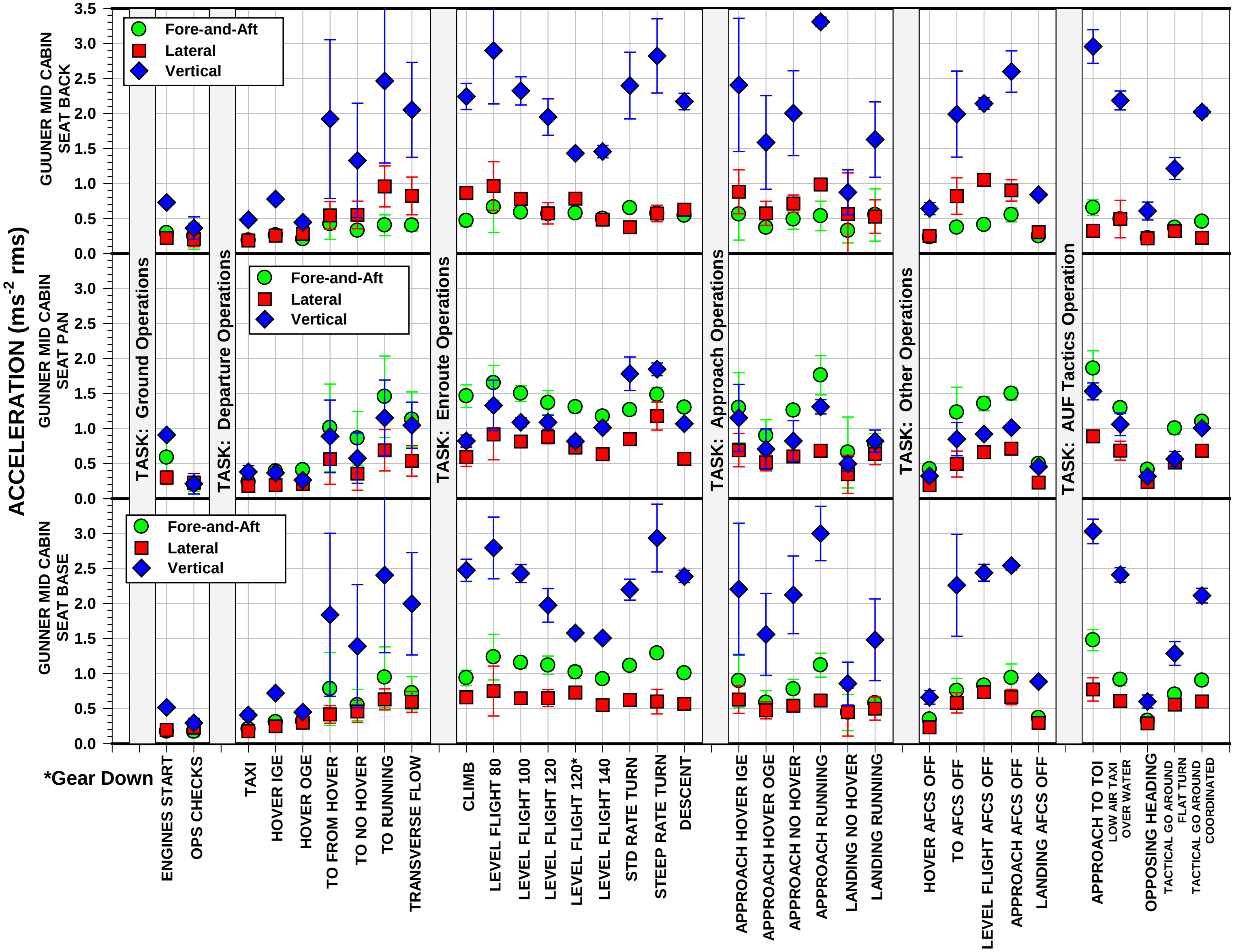


Figure A-7. Gunner Mean Overall Unweighted Accelerations ± One Standard Deviation

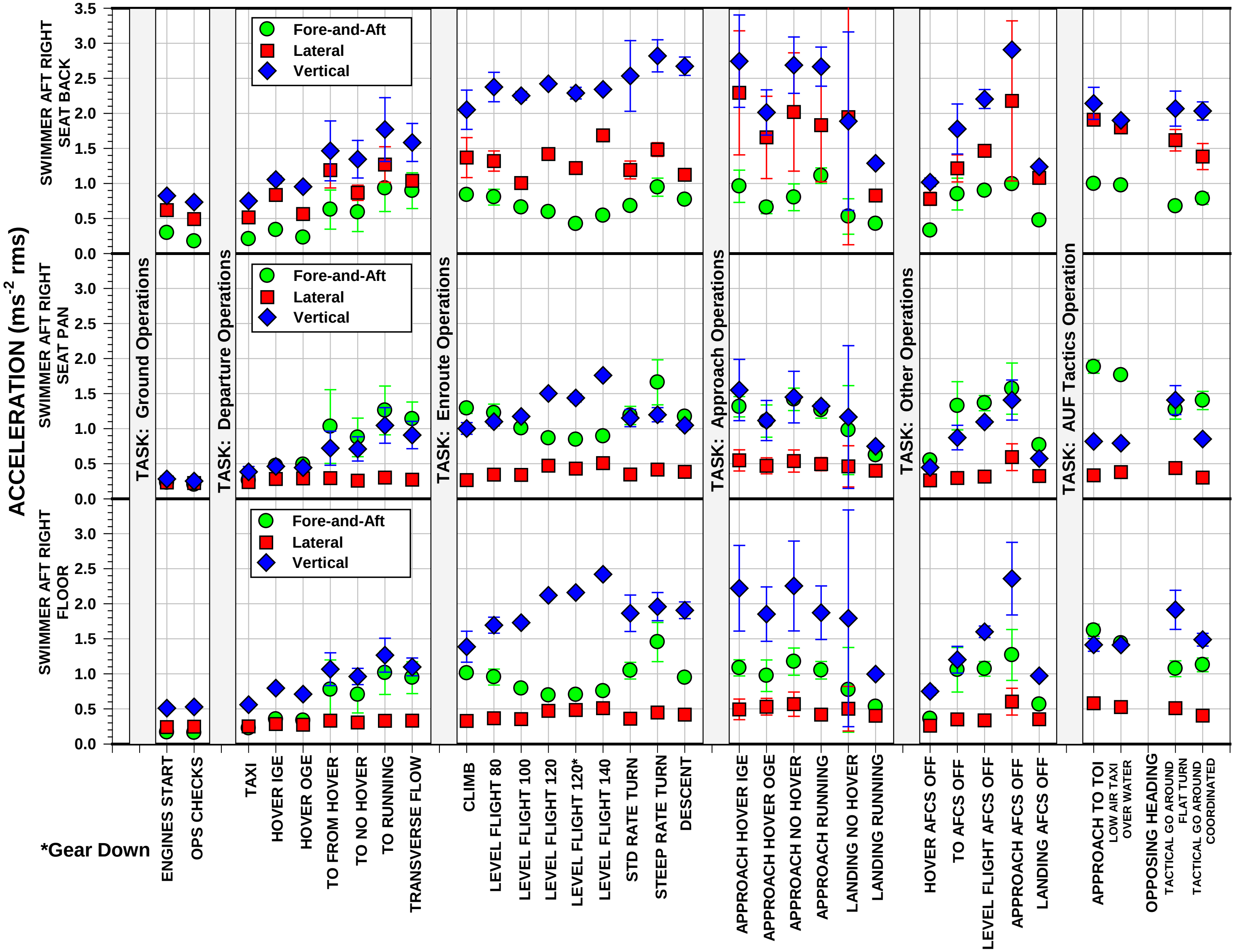


Figure A-8. Swimmer Mean Overall Unweighted Accelerations ± One Standard Deviation

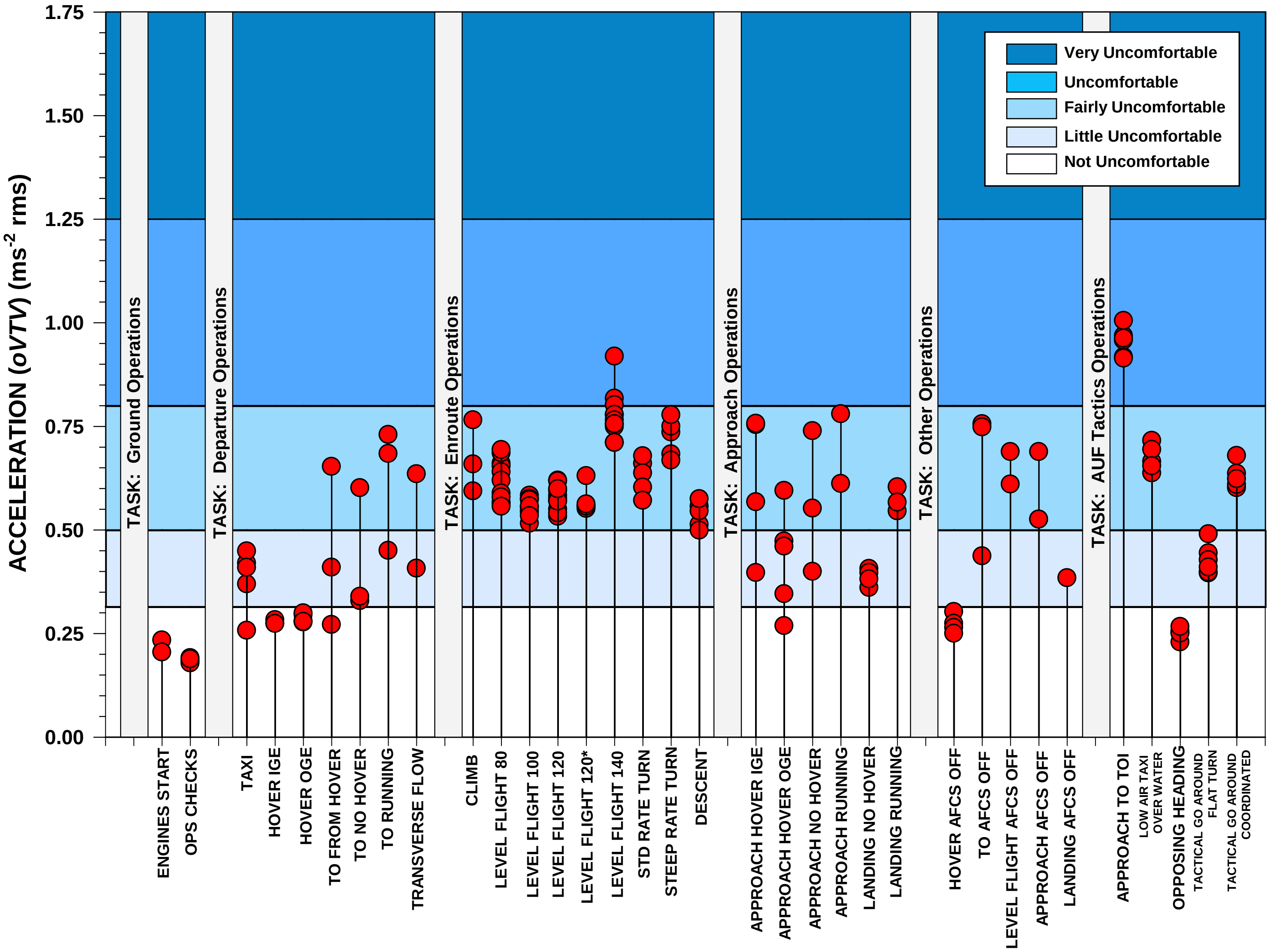


Figure A-9. Pilot Station Overall Vibration Total Values (*oVTVs*)

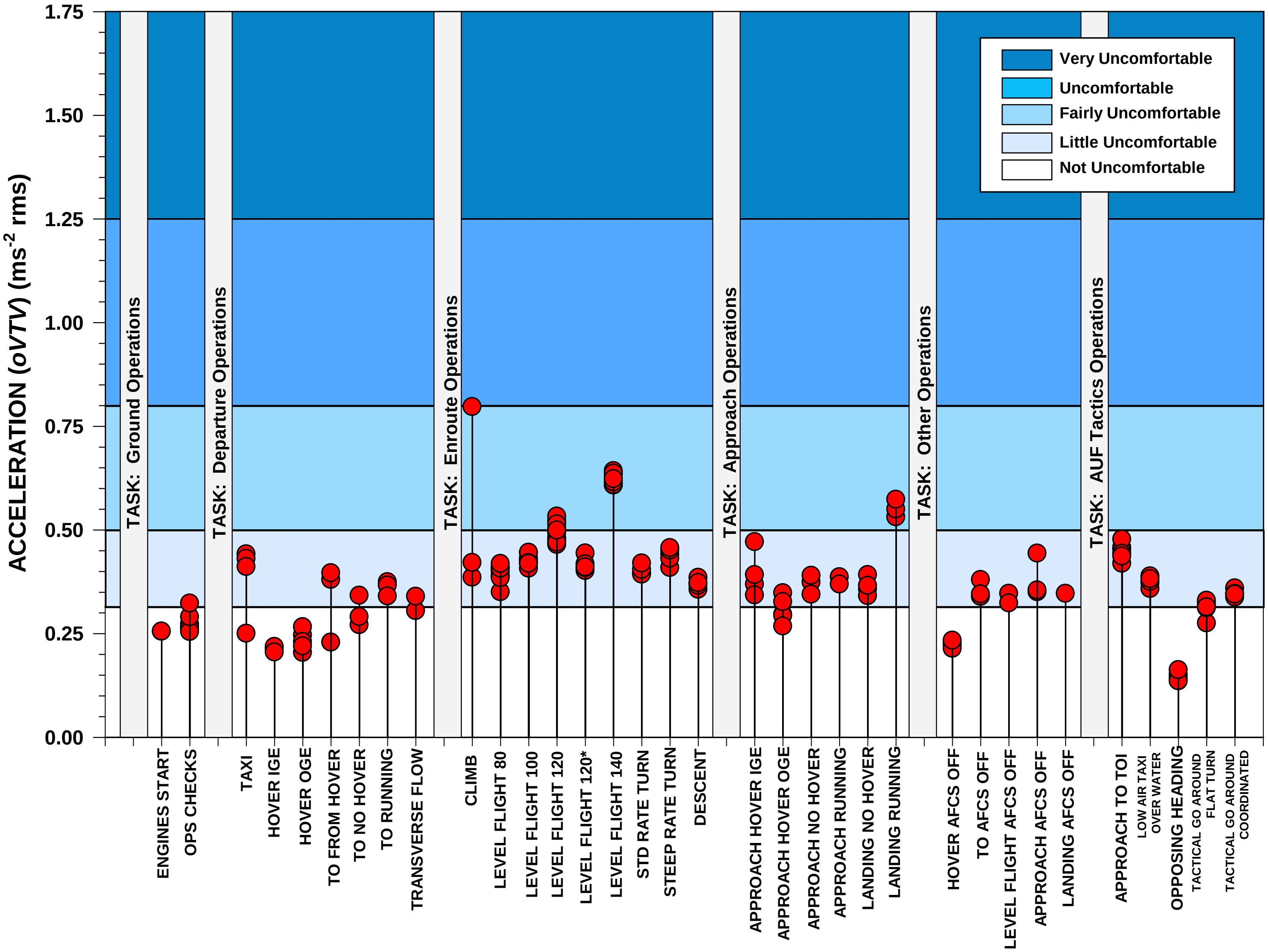


Figure A-10. Copilot Station Overall Vibration Total Values (*oVTVs*)

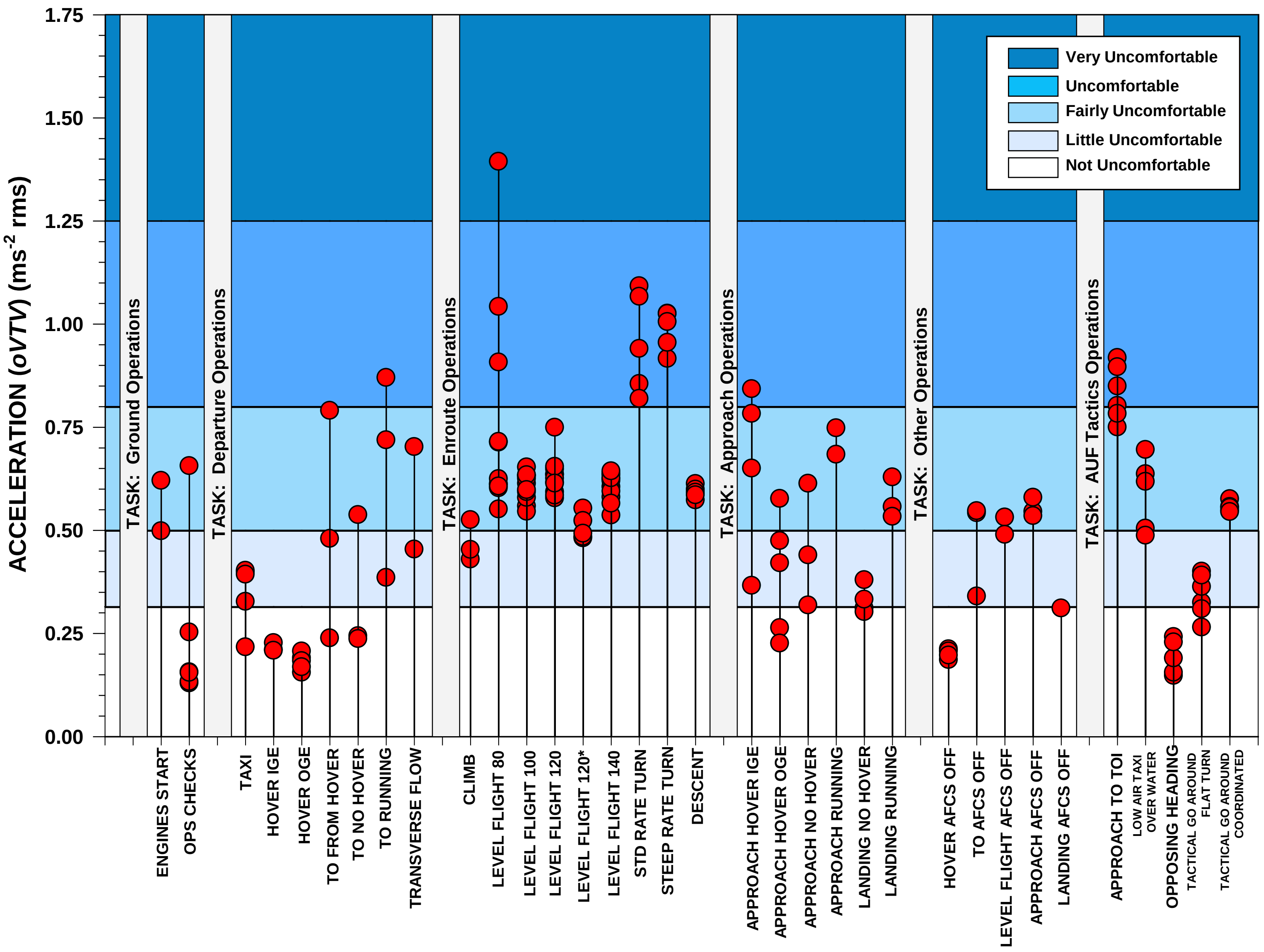


Figure A-11. Gunner Station Overall Vibration Total Values (*oVTVs*)

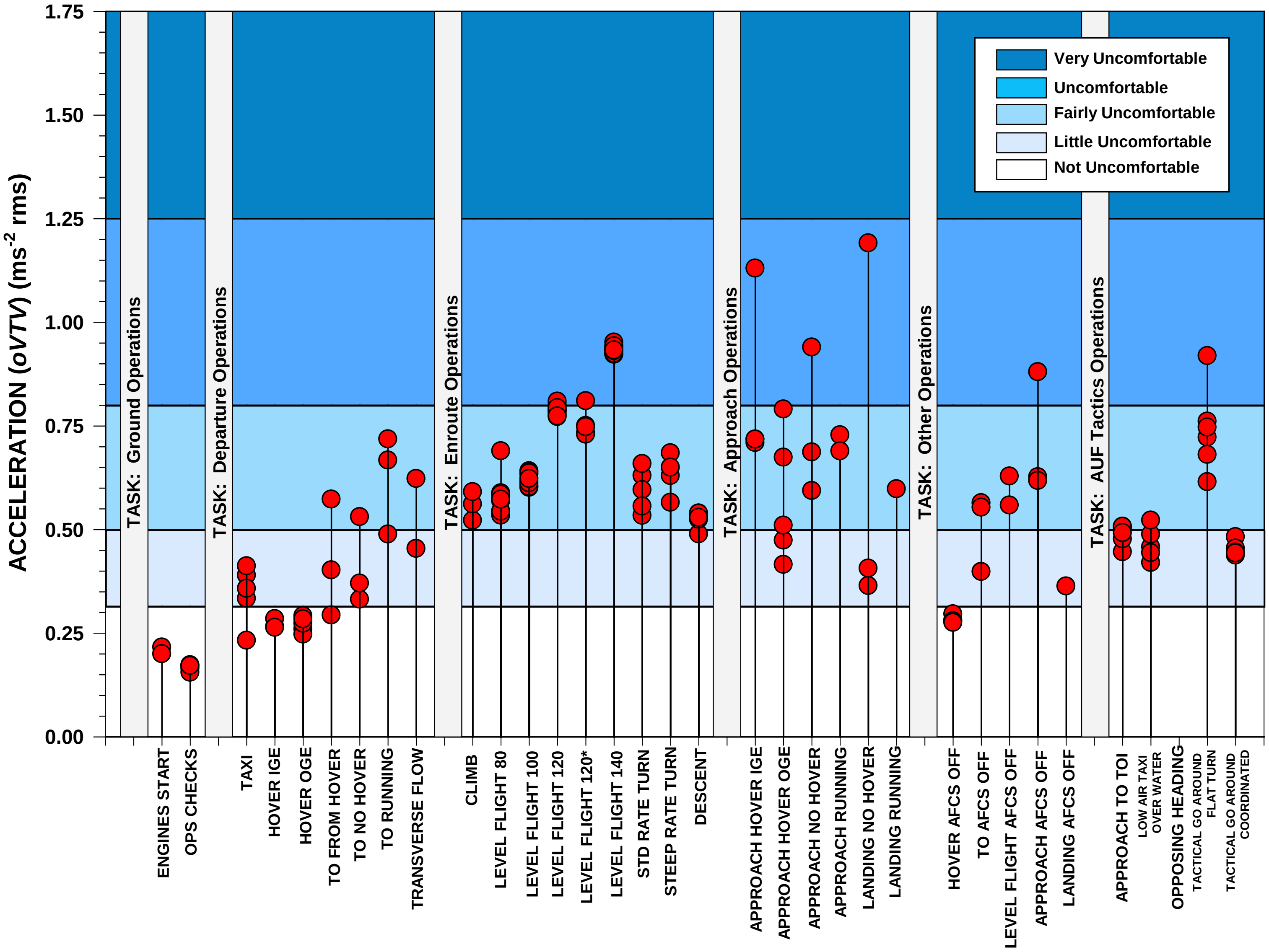
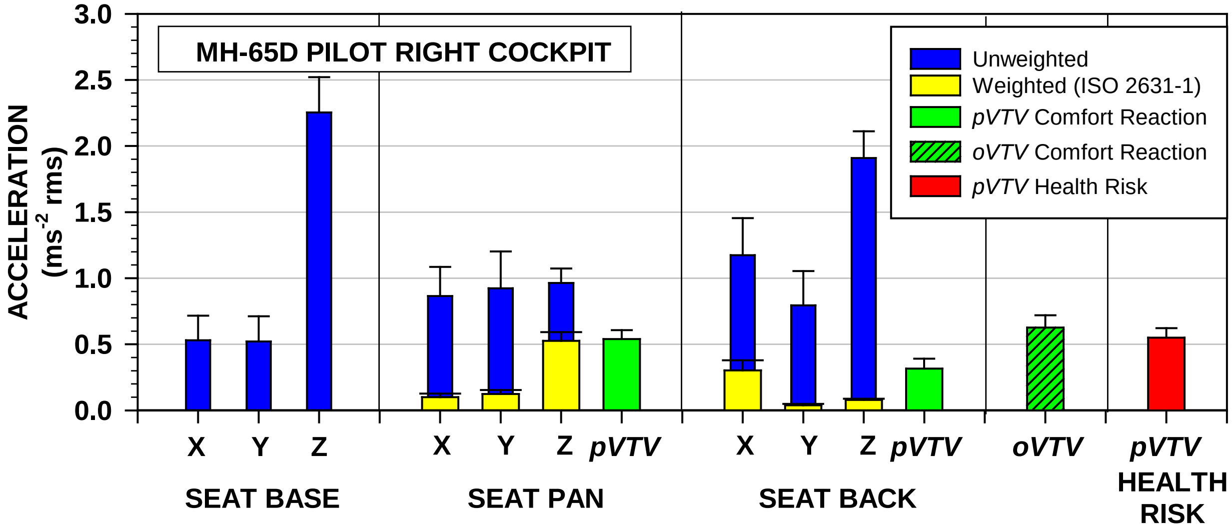


Figure A-12. Swimmer Station Overall Vibration Total Values (*oVTVs*)



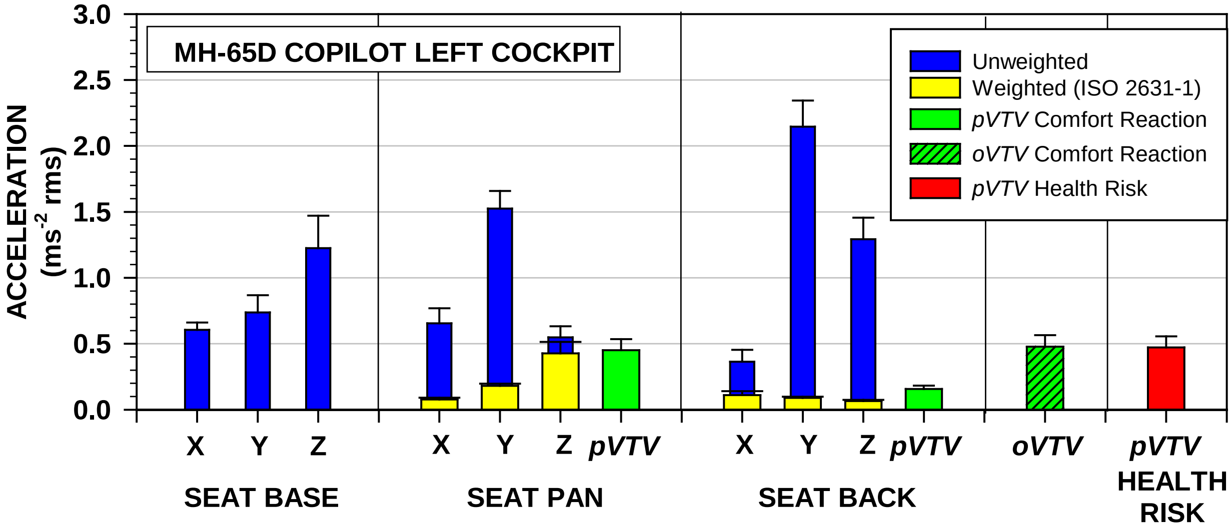
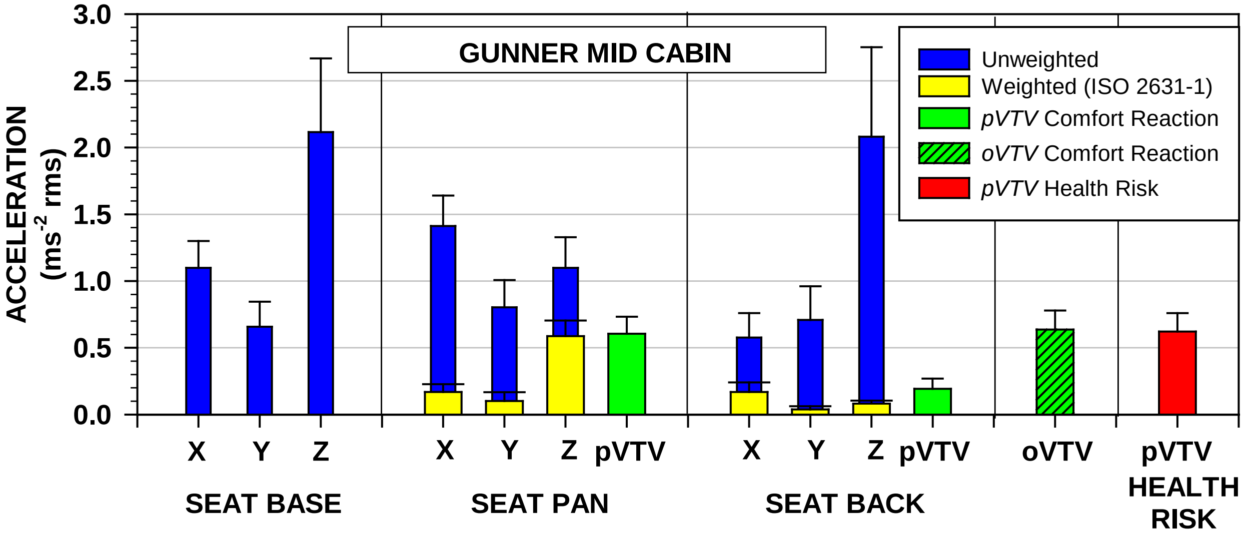


Figure A-13. Mean Unweighted and Weighted Accelerations, *pVTVs*, and *oVTVs* ± One Standard Deviation for Level Flight



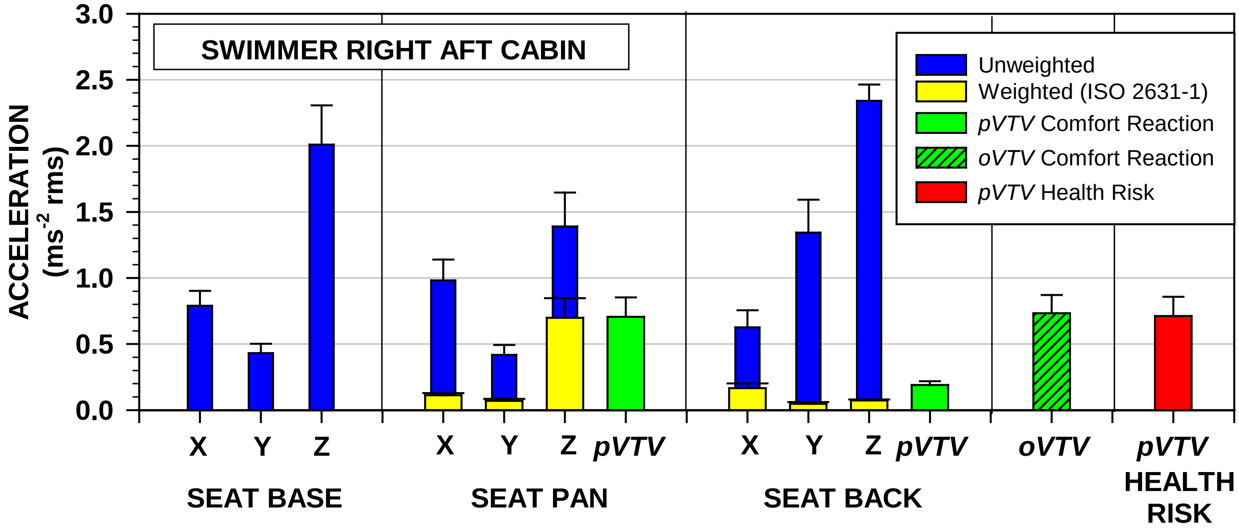


Figure A-13 (continued). Mean Unweighted and Weighted Accelerations, *pVTVs*, and *oVTVs* ± One Standard Deviation for Level Flight

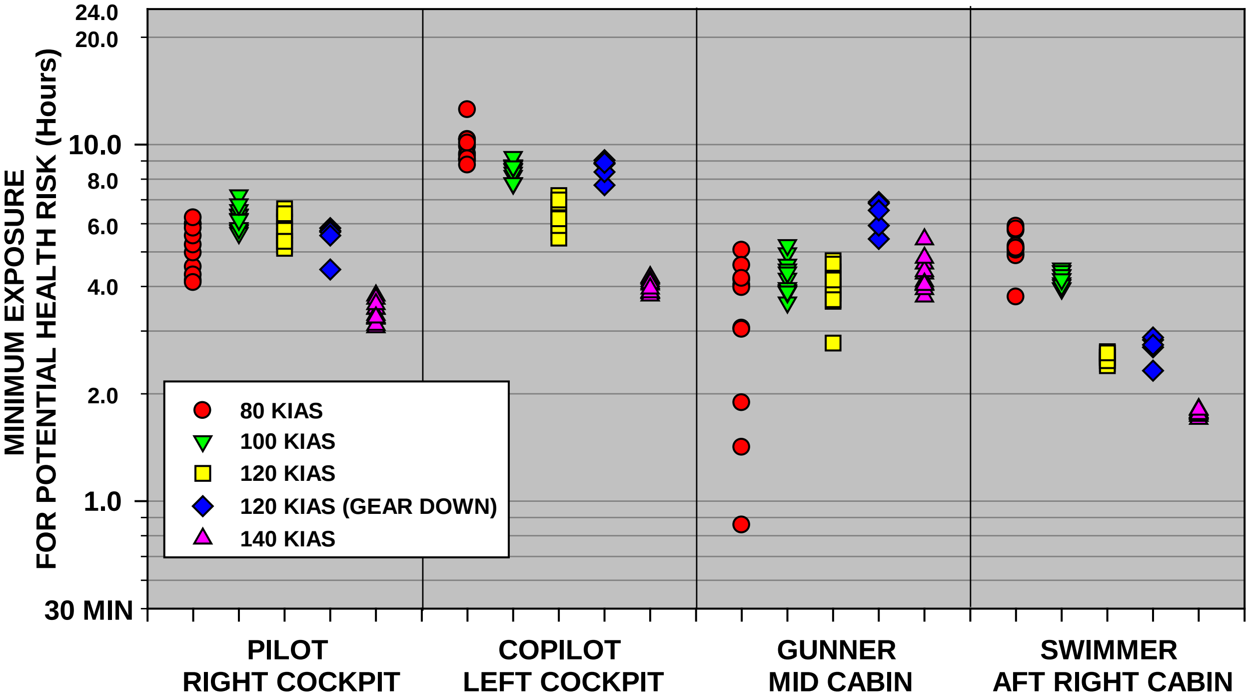


Figure A-14. Level Flight Minimum Exposure Durations for "Potential Health Risk" in a 24-Hour Period (ISO 2631-1)

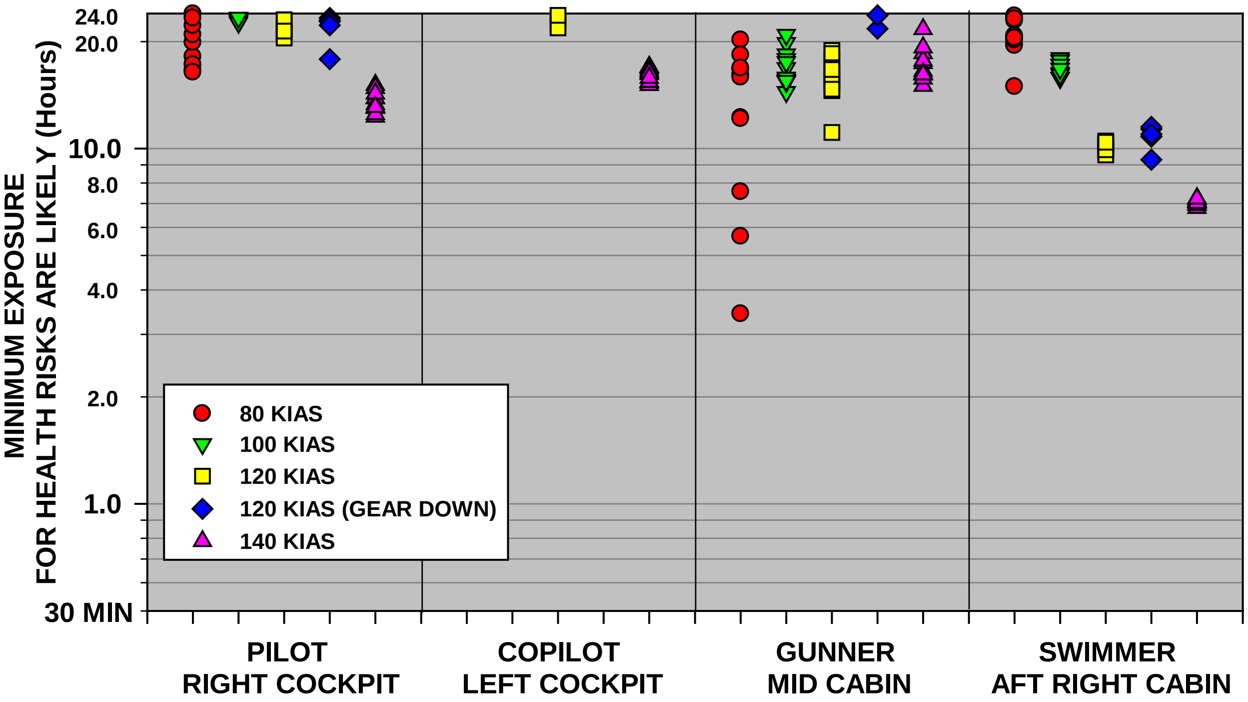


Figure A-15. Level Flight Minimum Exposure Durations for "Health Risks are Likely" in a 24-Hour Period (Hours)

Table A-1. REVER Component Details

Component	Dimensions (L/W/H cm)	Weight (Kg)	Item Identification
Large DAU	16.5/10.0/4.0	0.910 w/cables	EME S/N 98-11
Small DAUs	9.5/7.0/2.8	0.370 w/cables	EME S/N 04-22
			EME S/N 10-31
			EME S/N 10-41
Large Batteries	10.0/7.0/3.5	0.645	NA
Small Batteries	9.0/5.0/3.5	0.395	NA
Accelerometer Packs (Entran EGAX-25; TE Connectivity/Measurement Specialties EGAXT-25)	1.9 (diameter) 0.86 (thickness)	0.005 (0.060 w/ cable)	Pack AB
			Pack AC
			Pack N
			Pack K
			Pack Y
Accelerometer Pad (Entran EGAX-25; TE Connectivity/Measurement Specialties EGAXT-25) (Ride Quality Meter, RQM)	20.0 (diameter)	0.340 w/ cables	RQM 1 (Pack P)
			RQM 2 (Pack D)
			RQM 3 (Pack W)
			RQM 4 (Pack T)
			RQM 5 (Pack B)
			RQM 6 (Pack Q)
			RQM 7 (Pack J)
			RQM 8 (Pack G)
Triggers	7.6 (length) 2.2 (diameter)	0.030 w/cable	TRIG 1
			TRIG 2
			TRIG 3
			TRIG 4
Extra Cable	183 (length)	0.100	
Total Estimated Weight w/ two batteries + cable and two acceleration pads		2.23 – 2.77	

Table A-2. MH-65D Flight Tasks and Flight Test Condition Records

Task/Condition	# of Records	Bad Records
TASK: Ground Operations		
Engine(s) Start	2	
Operational Checks	6	
TASK: Departure Operations		
Taxi	5	
Hover (IGE)	3	
Hover (OGE)	5	
Takeoff (from hover)	3	
Takeoff (no hover)	3	
Takeoff (running)	3	
Transverse Flow	2	
TASK: Enroute Operations		
Climb	3	
Level Flight (80, 100, 120, 140 KIAS)	11 each airspeed	
Level Flight (120 KIAS Landing gear down)	5	
Standard Rate Turn	5	
Steep Rate Turn	5	
Descent	5	
TASK: Approach Operations		
Approach (hover IGE)	4	
Approach (hover OGE)	5	
Approach (no hover)	3	
Approach (running)	2	
Landing (no hover)	4	
Landing (running)	3-4	
TASK: Other Operations		
AFCS off (hover)	4	
AFCS off (takeoff)	3	
AFCS off (forward flight)	2	
AFCS off (approach)	3	
AFCS off (landing)	1	
TASK: AUF Tactics Operations		
Approach to TOI (out of trim)	6	
Signaling/Warning Shots (low air taxi over water)	5	
Opposing Heading (flying backwards)	5	
Tactical Go-Around (flat turn)	6	
Tactical Go-Around (Coordinated)	5	

AFCS: Automatic Flight Control System
AUF: Airborne Use of Force
IGE: In Ground Effect
KIAS: Knots Indicated Airspeed
OGE: Out of Ground Effect
TOI: Target of Interest

Table A-3. Pilot Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Minimum Exposure Durations for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	*pVTV*	POTENTIAL HLTH RISK WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISK PAN *pVTV*	HLTH RISKS LIKELY PAN *pVTV*
			ACCELERATION (ms^{-2} rms)							EXPOSURE DURATION (Hours)			
1	80	18	0.573	1.045	1.045	0.065	0.139	0.581	0.601	4.438	17.750	4.151	16.606
1	80	53	0.681	0.819	0.819	0.075	0.114	0.559	0.575	4.802	19.208	4.532	18.129
1	80	60	0.586	0.763	0.763	0.064	0.107	0.535	0.550	5.233	20.931	4.964	19.856
1	80	61	0.635	0.690	0.690	0.075	0.109	0.483	0.501	6.430	25.719	5.978	23.914
1	80	62	0.666	0.798	0.798	0.076	0.114	0.518	0.536	5.588	22.352	5.223	20.892
1	80	63	0.658	0.831	0.831	0.067	0.102	0.578	0.590	4.496	17.984	4.303	17.213
1	80	64	0.635	0.920	0.920	0.067	0.112	0.591	0.605	4.297	17.190	4.098	16.392
1	80	65	0.612	0.616	0.616	0.074	0.093	0.507	0.520	5.842	23.370	5.539	22.155
1	80	66	0.557	0.577	0.577	0.066	0.088	0.489	0.501	6.283	25.133	5.978	23.914
1	80	67	0.561	0.573	0.573	0.062	0.084	0.497	0.508	6.080	24.320	5.822	23.287
1	80	68	0.575	0.564	0.564	0.068	0.090	0.478	0.491	6.579	26.315	6.227	24.908
MEAN			0.613	0.745	0.745	0.069	0.105	0.529	0.543	5.461	21.843	5.165	20.661
STDEV			0.045	0.157	0.157	0.005	0.016	0.042	0.043	0.850	3.401	0.798	3.194
1	100	69	0.744	0.658	0.940	0.083	0.086	0.496	0.510	6.092	24.369	5.760	23.041
1	100	70	0.722	0.608	0.893	0.080	0.078	0.472	0.486	6.722	26.886	6.364	25.455
1	100	71	0.722	0.608	0.893	0.076	0.079	0.443	0.456	7.643	30.573	7.201	28.804
1	100	72	0.694	0.595	0.878	0.083	0.089	0.471	0.487	6.750	27.001	6.330	25.319
1	100	73	0.741	0.664	0.896	0.085	0.090	0.477	0.492	6.601	26.403	6.187	24.747
1	100	74	0.720	0.617	0.871	0.081	0.084	0.464	0.479	6.964	27.857	6.549	26.194
1	100	75	0.727	0.653	0.918	0.088	0.111	0.492	0.512	6.189	24.757	5.715	22.861
1	100	76	0.785	0.652	0.929	0.093	0.103	0.496	0.515	6.090	24.359	5.649	22.596
1	100	77	0.609	0.670	0.923	0.074	0.099	0.492	0.507	6.197	24.787	5.833	23.333
1	100	78	0.631	0.666	0.897	0.077	0.095	0.479	0.494	6.551	26.205	6.152	24.606
1	100	79	0.712	0.615	0.846	0.086	0.094	0.452	0.470	7.332	29.329	6.796	27.185
MEAN			0.710	0.637	0.898	0.082	0.092	0.476	0.492	6.648	26.593	6.230	24.922
STDEV			0.050	0.028	0.028	0.006	0.010	0.018	0.019	0.512	2.048	0.488	1.952
1	120	80	0.902	0.738	0.793	0.104	0.100	0.454	0.477	7.274	29.097	6.606	26.426
1	120	81	0.899	0.779	0.835	0.102	0.101	0.468	0.490	6.840	27.359	6.250	25.000
1	120	82	0.955	0.825	0.892	0.109	0.110	0.498	0.521	6.056	24.222	5.524	22.096
1	120	83	0.968	0.882	0.907	0.112	0.122	0.503	0.530	5.926	23.705	5.348	21.392
1	120	84	0.963	0.917	0.870	0.110	0.122	0.483	0.510	6.430	25.719	5.762	23.050
1	120	85	1.039	0.954	0.922	0.118	0.127	0.508	0.537	5.815	23.259	5.207	20.830
1	120	86	0.968	0.888	0.848	0.111	0.113	0.471	0.497	6.750	27.001	6.068	24.271
1	120	87	0.898	0.873	0.813	0.102	0.119	0.458	0.484	7.151	28.604	6.401	25.602
1	120	88	0.942	0.908	0.845	0.115	0.139	0.478	0.511	6.576	26.304	5.751	23.005
1	120	89	1.009	1.021	0.913	0.116	0.133	0.512	0.541	5.729	22.915	5.119	20.477
1	120	90	0.989	0.939	0.914	0.112	0.125	0.502	0.529	5.948	23.790	5.352	21.408
MEAN			0.957	0.884	0.868	0.110	0.119	0.485	0.512	6.409	25.634	5.763	23.051
STDEV			0.046	0.080	0.045	0.006	0.012	0.021	0.022	0.549	2.197	0.507	2.027
1	140	91	1.182	1.244	1.089	0.137	0.153	0.626	0.658	3.834	15.335	3.462	13.850
1	140	92	1.200	1.376	1.140	0.142	0.174	0.638	0.677	3.684	14.736	3.278	13.110
1	`40	93	1.197	1.384	1.191	0.139	0.168	0.664	0.699	3.406	13.625	3.074	12.298
1	140	94	1.176	1.312	1.107	0.136	0.162	0.623	0.658	3.871	15.484	3.470	13.879
1	140	95	1.214	1.310	1.142	0.140	0.159	0.637	0.671	3.700	14.801	3.333	13.330
1	140	96	1.175	1.291	1.143	0.137	0.161	0.646	0.679	3.599	14.395	3.251	13.003
1	140	97	1.124	1.285	1.029	0.130	0.155	0.597	0.630	4.209	16.835	3.777	15.108
1	140	98	1.128	1.315	1.027	0.132	0.166	0.601	0.637	4.158	16.633	3.699	14.796
1	140	99	1.179	1.428	1.085	0.141	0.179	0.607	0.648	4.072	16.290	3.570	14.280
1	140	100	1.270	1.425	1.180	0.150	0.181	0.652	0.693	3.531	14.123	3.124	12.497
1	140	101	1.264	1.402	1.155	0.146	0.171	0.638	0.677	3.680	14.722	3.275	13.099
MEAN			1.192	1.343	1.117	0.139	0.166	0.630	0.666	3.795	15.180	3.392	13.568
STDEV			0.046	0.062	0.055	0.006	0.009	0.021	0.022	0.261	1.044	0.225	0.902

Table A-4. Copilot Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Minimum Exposure Durations for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	*pVTV*	POTENTIAL HLTH RISK WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISK PAN *pVTV*	HLTH RISKS LIKELY PAN *pVTV*
			ACCELERATION (ms $^{-2}$ rms)							EXPOSURE DURATION (Hours)			
1	80	18	0.679	1.407	0.460	0.082	0.170	0.290	0.346	17.811	71.245	12.522	50.090
1	80	53	0.688	1.365	0.523	0.075	0.161	0.338	0.381	13.169	52.675	10.323	41.290
1	80	60	0.577	1.335	0.500	0.064	0.161	0.340	0.382	12.953	51.812	10.295	41.182
1	80	61	0.543	1.352	0.507	0.062	0.167	0.357	0.399	11.750	46.999	9.413	37.650
1	80	62	0.606	1.308	0.522	0.066	0.160	0.350	0.390	12.280	49.120	9.857	39.428
1	80	63	0.696	1.464	0.533	0.077	0.165	0.358	0.402	11.684	46.737	9.287	37.146
1	80	64	0.623	1.491	0.509	0.069	0.170	0.339	0.386	13.052	52.210	10.088	40.353
1	80	65	0.557	1.460	0.508	0.064	0.173	0.363	0.407	11.402	45.610	9.055	36.221
1	80	66	0.533	1.397	0.496	0.062	0.163	0.369	0.408	11.028	44.113	9.015	36.062
1	80	67	0.590	1.397	0.503	0.067	0.164	0.365	0.406	11.247	44.987	9.109	36.436
1	80	68	0.539	1.423	0.507	0.062	0.168	0.373	0.414	10.770	43.079	8.756	35.024
MEAN			0.603	1.400	0.506	0.068	0.166	0.349	0.393	12.468	49.871	9.793	39.171
STDEV			0.061	0.057	0.019	0.007	0.004	0.023	0.019	1.959	7.835	1.057	4.227
1	100	69	0.528	1.424	0.511	0.062	0.164	0.381	0.419	10.355	41.420	8.544	34.176
1	100	70	0.527	1.418	0.515	0.063	0.162	0.392	0.429	9.767	39.066	8.166	32.662
1	100	71	0.528	1.413	0.508	0.063	0.163	0.382	0.420	10.290	41.160	8.503	34.014
1	100	72	0.533	1.455	0.524	0.068	0.170	0.383	0.424	10.247	40.988	8.336	33.343
1	100	73	0.519	1.406	0.498	0.061	0.163	0.376	0.414	10.621	42.485	8.739	34.956
1	100	74	0.533	1.356	0.501	0.062	0.158	0.379	0.415	10.465	41.859	8.714	34.855
1	100	75	0.555	1.394	0.540	0.067	0.172	0.399	0.439	9.446	37.783	7.780	31.119
1	100	76	0.536	1.429	0.550	0.065	0.176	0.397	0.439	9.541	38.165	7.797	31.190
1	100	77	0.549	1.436	0.533	0.065	0.169	0.375	0.416	10.689	42.758	8.664	34.654
1	100	78	0.544	1.429	0.520	0.063	0.168	0.361	0.403	11.510	46.040	9.236	36.944
1	100	79	0.492	1.414	0.503	0.060	0.176	0.372	0.416	10.869	43.474	8.684	34.738
MEAN			0.531	1.416	0.518	0.063	0.167	0.381	0.421	10.345	41.382	8.469	33.877
STDEV			0.017	0.025	0.017	0.002	0.006	0.011	0.011	0.604	2.414	0.430	1.719
1	120	80	0.606	1.474	0.511	0.069	0.172	0.448	0.485	7.480	29.921	6.385	25.539
1	120	81	0.611	1.496	0.512	0.070	0.174	0.436	0.475	7.891	31.563	6.659	26.638
1	120	82	0.607	1.467	0.559	0.070	0.174	0.479	0.514	6.549	26.194	5.678	22.710
1	120	83	0.608	1.486	0.575	0.070	0.179	0.487	0.524	6.317	25.267	5.463	21.852
1	120	84	0.645	1.502	0.535	0.078	0.180	0.412	0.457	8.824	35.296	7.195	28.779
1	120	85	0.632	1.528	0.524	0.073	0.181	0.422	0.465	8.435	33.740	6.940	27.761
1	120	86	0.625	1.549	0.510	0.075	0.184	0.424	0.468	8.352	33.406	6.849	27.394
1	120	87	0.638	1.538	0.515	0.074	0.184	0.419	0.463	8.556	34.225	6.991	27.965
1	120	88	0.642	1.517	0.565	0.079	0.188	0.446	0.490	7.544	30.177	6.237	24.949
1	120	89	0.631	1.529	0.565	0.077	0.183	0.463	0.503	7.012	28.050	5.926	23.705
1	120	90	0.621	1.539	0.535	0.075	0.183	0.450	0.492	7.398	29.590	6.197	24.787
MEAN			0.624	1.511	0.537	0.074	0.180	0.444	0.485	7.669	30.675	6.411	25.644
STDEV			0.015	0.028	0.025	0.003	0.005	0.025	0.022	0.828	3.314	0.569	2.274
1	140	91	0.819	1.590	0.688	0.097	0.188	0.586	0.623	4.365	17.461	3.861	15.444
1	140	92	0.846	1.622	0.685	0.100	0.198	0.567	0.609	4.672	18.690	4.051	16.204
1	140	93	0.851	1.731	0.674	0.099	0.204	0.552	0.597	4.916	19.663	4.206	16.823
1	140	94	0.848	1.707	0.673	0.098	0.201	0.551	0.595	4.937	19.748	4.240	16.959
1	140	95	0.833	1.698	0.676	0.096	0.200	0.552	0.594	4.932	19.727	4.248	16.994
1	140	96	0.842	1.683	0.686	0.098	0.201	0.559	0.602	4.805	19.222	4.142	16.567
1	140	97	0.828	1.718	0.691	0.096	0.201	0.563	0.606	4.729	18.916	4.090	16.360
1	140	98	0.838	1.649	0.718	0.099	0.199	0.585	0.626	4.386	17.544	3.834	15.335
1	140	99	0.830	1.666	0.711	0.100	0.202	0.589	0.630	4.328	17.313	3.774	15.098
1	140	100	0.802	1.682	0.694	0.095	0.203	0.583	0.624	4.419	17.677	3.851	15.404
1	140	101	0.826	1.792	0.663	0.096	0.211	0.571	0.616	4.601	18.403	3.950	15.802
MEAN			0.833	1.685	0.687	0.097	0.201	0.569	0.611	4.645	18.578	4.023	16.090
STDEV			0.014	0.055	0.016	0.002	0.005	0.015	0.013	0.239	0.958	0.176	0.703

Table A-5. Gunner Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Minimum Exposure Durations for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	*pVTV*	POTENTIAL HLTH RISK WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISK PAN *pVTV*	HLTH RISKS LIKELY PAN *pVTV*
			ACCELERATION (ms $^{-2}$ rms)							EXPOSURE DURATION (Hours)			
1	80	18	1.432	0.777	1.121	0.175	0.087	0.578	0.610	4.496	17.984	4.035	16.141
1	80	53	2.176	1.834	2.007	0.540	0.528	1.086	1.323	1.271	5.085	0.857	3.428
1	80	60	1.482	0.679	1.107	0.167	0.080	0.571	0.600	4.605	18.422	4.167	16.667
1	80	61	1.689	0.639	0.990	0.191	0.080	0.504	0.545	5.900	23.602	5.050	20.200
1	80	62	1.672	0.688	1.035	0.191	0.088	0.532	0.572	5.300	21.200	4.583	18.332
1	80	63	1.999	1.347	1.906	0.227	0.157	0.992	1.030	1.524	6.097	1.415	5.660
1	80	64	1.780	0.937	1.654	0.201	0.119	0.860	0.891	2.028	8.112	1.889	7.554
1	80	65	1.560	0.856	1.294	0.176	0.099	0.671	0.701	3.330	13.318	3.054	12.217
1	80	66	1.384	0.714	1.136	0.166	0.096	0.584	0.615	4.395	17.580	3.970	15.879
1	80	67	1.549	0.849	1.307	0.177	0.107	0.672	0.703	3.319	13.275	3.033	12.130
1	80	68	1.450	0.765	1.087	0.170	0.100	0.564	0.597	4.724	18.896	4.210	16.840
MEAN			1.652	0.917	1.331	0.216	0.140	0.692	0.744	3.718	14.870	3.297	13.186
STDEV			0.249	0.361	0.359	0.109	0.131	0.198	0.243	1.552	6.209	1.376	5.502
1	100	69	1.600	0.766	1.003	0.180	0.081	0.514	0.550	5.684	22.737	4.953	19.813
1	100	70	1.465	0.748	0.977	0.165	0.081	0.503	0.536	5.922	23.686	5.223	20.892
1	100	71	1.584	0.876	1.089	0.179	0.099	0.561	0.597	4.766	19.065	4.209	16.835
1	100	72	1.688	0.841	1.173	0.192	0.097	0.608	0.645	4.059	16.236	3.607	14.427
1	100	73	1.504	0.876	1.141	0.173	0.110	0.590	0.624	4.315	17.260	3.851	15.404
1	100	74	1.353	0.786	1.047	0.153	0.085	0.544	0.571	5.076	20.305	4.602	18.409
1	100	75	1.440	0.818	1.052	0.164	0.098	0.547	0.580	5.008	20.031	4.464	17.854
1	100	76	1.337	0.844	1.136	0.155	0.108	0.591	0.620	4.299	17.196	3.901	15.604
1	100	77	1.559	0.812	1.128	0.176	0.092	0.583	0.616	4.416	17.665	3.959	15.838
1	100	78	1.569	0.830	1.148	0.176	0.091	0.590	0.622	4.311	17.242	3.875	15.499
1	100	79	1.405	0.771	1.078	0.161	0.090	0.556	0.586	4.857	19.430	4.376	17.502
MEAN			1.500	0.815	1.088	0.170	0.094	0.562	0.595	4.792	19.168	4.274	17.098
STDEV			0.111	0.044	0.063	0.012	0.010	0.034	0.034	0.599	2.395	0.504	2.017
1	120	80	1.605	1.104	1.084	0.185	0.110	0.580	0.619	4.456	17.824	3.917	15.669
1	120	81	1.628	0.853	0.964	0.184	0.082	0.526	0.564	5.413	21.653	4.724	18.896
1	120	82	1.445	0.793	1.011	0.171	0.101	0.549	0.584	4.970	19.878	4.397	17.586
1	120	83	1.428	0.843	0.987	0.162	0.090	0.539	0.570	5.171	20.683	4.623	18.493
1	120	84	1.454	0.944	1.094	0.166	0.125	0.591	0.626	4.300	17.201	3.828	15.311
1	120	85	1.466	1.009	1.133	0.167	0.108	0.611	0.642	4.023	16.093	3.637	14.548
1	120	86	1.276	0.826	1.033	0.168	0.143	0.554	0.596	4.894	19.578	4.223	16.891
1	120	87	1.245	0.830	1.100	0.147	0.105	0.584	0.612	4.397	17.586	4.011	16.046
1	120	88	1.152	0.819	1.162	0.137	0.096	0.617	0.639	3.942	15.766	3.671	14.685
1	120	89	1.137	0.797	1.080	0.128	0.089	0.579	0.600	4.477	17.910	4.174	16.694
1	120	90	1.208	0.881	1.336	0.159	0.118	0.708	0.735	2.993	11.973	2.777	11.106
MEAN			1.368	0.882	1.089	0.161	0.106	0.585	0.617	4.458	17.831	3.998	15.993
STDEV			0.173	0.098	0.102	0.018	0.018	0.050	0.047	0.671	2.684	0.541	2.162
1	140	91	1.218	0.683	1.105	0.141	0.080	0.611	0.632	4.014	16.056	3.752	15.007
1	140	92	1.176	0.648	0.890	0.137	0.085	0.501	0.526	5.986	23.943	5.422	21.686
1	`40	93	1.179	0.666	0.985	0.138	0.080	0.546	0.569	5.032	20.126	4.638	18.552
1	140	94	1.157	0.660	1.010	0.141	0.089	0.563	0.587	4.731	18.923	4.350	17.401
1	140	95	1.171	0.624	1.042	0.131	0.068	0.584	0.602	4.400	17.598	4.135	16.540
1	140	96	1.206	0.633	1.001	0.133	0.073	0.562	0.583	4.742	18.970	4.421	17.683
1	140	97	1.188	0.611	1.020	0.136	0.069	0.587	0.607	4.350	17.401	4.074	16.295
1	140	98	1.140	0.612	1.065	0.136	0.075	0.598	0.618	4.199	16.795	3.933	15.730
1	140	99	1.186	0.612	0.960	0.134	0.069	0.537	0.558	5.194	20.776	4.814	19.256
1	140	100	1.181	0.622	1.031	0.134	0.077	0.589	0.609	4.327	17.307	4.047	16.188
1	140	101	1.112	0.615	1.025	0.130	0.083	0.589	0.609	4.319	17.277	4.042	16.167
MEAN			1.174	0.635	1.012	0.135	0.077	0.570	0.591	4.663	18.652	4.330	17.319
STDEV			0.029	0.025	0.056	0.004	0.007	0.032	0.031	0.567	2.267	0.478	1.913

Table A-6. Swimmer Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Minimum Exposure Durations for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	*pVTV*	POTENTIAL HLTH RISK WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISK PAN *pVTV*	HLTH RISKS LIKELY PAN *pVTV*
			ACCELERATION (ms $^{-2}$ rms)							EXPOSURE DURATION (Hours)			
1	80	18	1.261	0.296	1.227	0.140	0.051	0.616	0.634	3.953	15.812	3.735	14.941
1	80	53	1.332	0.365	1.120	0.147	0.070	0.527	0.552	5.393	21.571	4.925	19.698
1	80	60	1.227	0.313	1.017	0.139	0.054	0.490	0.512	6.252	25.010	5.724	22.897
1	80	61	1.104	0.335	1.115	0.124	0.075	0.536	0.555	5.231	20.923	4.871	19.486
1	80	62	1.212	0.396	1.156	0.134	0.067	0.524	0.545	5.463	21.852	5.052	20.208
1	80	63	1.480	0.375	1.102	0.164	0.045	0.513	0.541	5.693	22.772	5.131	20.523
1	80	64	1.366	0.347	1.076	0.152	0.045	0.519	0.543	5.562	22.249	5.087	20.349
1	80	65	1.098	0.332	1.098	0.122	0.078	0.518	0.538	5.592	22.370	5.190	20.760
1	80	66	1.100	0.335	1.035	0.123	0.060	0.485	0.504	6.369	25.476	5.900	23.602
1	80	67	1.198	0.361	1.045	0.133	0.050	0.489	0.509	6.278	25.112	5.792	23.168
1	80	68	1.097	0.338	1.110	0.122	0.062	0.524	0.541	5.465	21.860	5.117	20.470
MEAN			1.225	0.345	1.100	0.136	0.060	0.522	0.543	5.568	22.273	5.139	20.555
STDEV			0.127	0.028	0.059	0.014	0.012	0.036	0.035	0.664	2.655	0.587	2.349
1	100	69	1.022	0.326	1.162	0.115	0.046	0.578	0.591	4.490	17.960	4.292	17.167
1	100	70	1.005	0.317	1.142	0.114	0.041	0.565	0.578	4.696	18.782	4.490	17.960
1	100	71	0.994	0.332	1.151	0.112	0.050	0.570	0.583	4.620	18.480	4.415	17.659
1	100	72	0.988	0.348	1.180	0.113	0.066	0.584	0.598	4.404	17.617	4.193	16.773
1	100	73	0.932	0.348	1.154	0.105	0.058	0.570	0.583	4.618	18.474	4.421	17.683
1	100	74	0.975	0.358	1.170	0.111	0.047	0.578	0.590	4.490	17.960	4.303	17.213
1	100	75	1.011	0.364	1.205	0.117	0.077	0.600	0.616	4.169	16.678	3.953	15.812
1	100	76	0.988	0.365	1.216	0.112	0.087	0.600	0.616	4.172	16.689	3.950	15.802
1	100	77	1.117	0.340	1.187	0.127	0.071	0.588	0.606	4.333	17.330	4.085	16.338
1	100	78	1.081	0.328	1.186	0.123	0.069	0.593	0.610	4.261	17.045	4.034	16.135
1	100	79	0.961	0.327	1.178	0.109	0.061	0.585	0.598	4.380	17.520	4.189	16.756
MEAN			1.007	0.341	1.175	0.114	0.061	0.583	0.597	4.421	17.685	4.211	16.845
STDEV			0.052	0.017	0.023	0.006	0.015	0.012	0.014	0.180	0.720	0.190	0.760
1	120	80	0.862	0.503	1.477	0.098	0.065	0.747	0.756	2.690	10.758	2.625	10.501
1	120	81	0.879	0.481	1.488	0.099	0.065	0.751	0.760	2.659	10.635	2.595	10.380
1	120	82	0.867	0.477	1.493	0.098	0.072	0.755	0.765	2.630	10.520	2.563	10.252
1	120	83	0.866	0.473	1.499	0.100	0.081	0.759	0.770	2.606	10.423	2.533	10.133
1	120	84	0.842	0.473	1.506	0.096	0.074	0.761	0.771	2.587	10.350	2.523	10.094
1	120	85	0.842	0.465	1.515	0.097	0.068	0.769	0.778	2.539	10.157	2.481	9.923
1	120	86	0.851	0.465	1.504	0.097	0.058	0.761	0.769	2.591	10.366	2.536	10.143
1	120	87	0.867	0.465	1.530	0.099	0.070	0.776	0.785	2.494	9.977	2.434	9.737
1	120	88	0.873	0.463	1.532	0.102	0.097	0.778	0.791	2.478	9.913	2.400	9.599
1	120	89	0.879	0.465	1.508	0.101	0.084	0.767	0.778	2.552	10.210	2.479	9.918
1	120	90	0.881	0.471	1.477	0.101	0.071	0.749	0.759	2.677	10.707	2.606	10.423
MEAN			0.864	0.473	1.503	0.099	0.073	0.761	0.771	2.591	10.365	2.525	10.100
STDEV			0.014	0.012	0.018	0.002	0.011	0.010	0.011	0.070	0.282	0.071	0.286
1	140	91	0.927	0.492	1.737	0.103	0.077	0.900	0.909	1.851	7.402	1.814	7.255
1	140	92	0.946	0.543	1.791	0.107	0.088	0.929	0.939	1.740	6.960	1.702	6.809
1	`40	93	0.903	0.519	1.773	0.101	0.081	0.920	0.929	1.773	7.093	1.738	6.954
1	140	94	0.890	0.512	1.764	0.099	0.072	0.914	0.922	1.796	7.182	1.764	7.057
1	140	95	0.883	0.500	1.745	0.099	0.070	0.904	0.912	1.837	7.347	1.804	7.217
1	140	96	0.885	0.487	1.756	0.099	0.078	0.909	0.918	1.815	7.260	1.781	7.123
1	140	97	0.878	0.501	1.764	0.097	0.068	0.912	0.920	1.802	7.209	1.773	7.090
1	140	98	0.898	0.543	1.775	0.101	0.087	0.920	0.930	1.773	7.090	1.736	6.945
1	140	99	0.883	0.516	1.753	0.100	0.087	0.910	0.919	1.813	7.253	1.776	7.104
1	140	100	0.876	0.488	1.765	0.103	0.095	0.913	0.924	1.798	7.192	1.757	7.026
1	140	101	0.860	0.503	1.743	0.095	0.079	0.903	0.911	1.841	7.363	1.807	7.230
MEAN			0.894	0.509	1.760	0.100	0.080	0.912	0.921	1.803	7.214	1.768	7.074
STDEV			0.024	0.020	0.016	0.003	0.008	0.008	0.009	0.033	0.132	0.034	0.136

Table A-7. Statistical Results for Directional Effects.
Significant differences at P<0.05.

	Pilot			Copilot		
	Seat Base	Seat Pan	Seat Back	Seat Base	Seat Pan	Seat Back
80 KIAS	Z>(X=Y)	(Y=Z)>X	Z>X>Y	Z>X>Y	Y>X>Z	Y>Z>X
100 KIAS	Z>(X=Y)	Z>Y>X	Z>X>Y	Z>(X=Y)	Y>(X=Z)	Y>Z>X
120 KIAS	Z>(X=Y)	X>(Y=Z)	Z>X>Y	Z>Y>X	Y>X>Z	Y>Z>X
140 KIAS	Z>(X=Y)	Y>X>Z	Z>X>Y	Y>Z>X	Y>X>Z	Y>Z>X
	Gunner			**Swimmer**		
	Seat Base	Seat Pan	Seat Back	Floor	Seat Pan	Seat Back
80 KIAS	Z>X>Y	X>Z>Y	Z>(X=Y)	Z>X>Y	X>Z>Y	Z>Y>X
100 KIAS	Z>X>Y	X>Z>Y	Z>Y>X	Z>X>Y	Z>X>Y	Z>Y>X
120 KIAS	Z>X>Y	X>Z>Y	Z>(X=Y)	Z>X>Y	Z>X>Y	Z>Y>X
140 KIAS	Z>X>Y	X>Z>Y	Z>(X=Y)	Z>X>Y	Z>X>Y	Z>Y>X

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711 Human Performance Wing
AFCS	Automatic Flight Control System
AFRL	Air Force Research Laboratory
AFRLI	Air Force Research Laboratory Instruction
APHC	Army Public Health Center
ARNG	Army National Guard
AUF	Airborne Use of Force
BCA	Business Case Analysis
BPF	Blade Passage Frequency
CBDN	Collaborative Biomechanics Data Network
DAU	Data Acquisition Unit
FTP	Flight Test Plan
HGCZs	Health Guidance Caution Zones (ISO 2631-1, Annex B)
Hz	Herz (cycles per second)
IGE	In Ground Effect
ISO	International Organization for Standardization
KIAS	Knots Indicated Airspeed
MIL-STD	Military Standard
MOA	Memorandum of Agreement
NDCEE	National Defense Center for Energy and Environment
OGE	Out of Ground Effect
OUSD ATL	Under Secretary of Defense for Acquisition, Technology and Logistics
PRF	Propeller Rotation Frequency
REVER	Remote Vibration Environment Recorder
RH	Airman Systems Directorate
SRB	Safety Review Board
TO	Take-Off
TOI	Target of Interest
TRB	Technical Review Board
USCG	United States Coast Guard
rms	Root-Mean-Square

a_{rms}	Root-Mean-Square Acceleration
a_{uw}	Overall Unweighted Acceleration Level
a_w	Overall Weighted Acceleration Level
k	Multiplying Factor (ISO 2631-1)
$oVTV$	Overall Vibration Total Value
$pVTV$	Point Vibration Total Value
W	Frequency Weighting (ISO 2631-1)