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**AIRCREW VIBRATION EXPOSURE CHARACTERIZATION
AND HEALTH RISK ASSESSMENT OF THE CV-22 OSPREY**

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14. ABSTRACT This study characterized and assessed aircrew vibration exposure aboard the CV-22 Osprey tilt-rotor aircraft owned and operated by the 20 th Special Operations Squadron located at Cannon AFB, NM. The ISO 2631-1: 1997, and other related standards, were used as the guidelines. Triaxial accelerations were collected at the seat base/rigid structure, seat pan, seat back, and helmet (pilot only) at the pilot, flight engineer (FE), and cabin aircrew stations. Multiple data records were collected for typical aircraft flight conditions. Acceleration spectra, and the overall unweighted and weighted accelerations (1-80 Hz) were calculated for all records. During airplane (APLN) mode, multi-axis acceleration peaks were observed at 16.5 Hz and associated with the blade passage frequency (BPF) (84% RPM). During conversion (CONV) mode, multi-axis peaks was observed at 20 Hz (BPF at 100% RPM). Both modes showed notable peaks at multiples of the BPF. For all data records, the seat pan and seat back point vibration total values (pVTVs) were calculated (vector sum of the overall weighted accelerations in three directions (X, Y, Z)). The overall vibration total values (oVTVs) for assessing comfort reaction (ISO 2631-1) was calculated as the vector sum of these pVTVs. The comfort reactions at the pilot and FE stations ranged from “a little uncomfortable” to “fairly uncomfortable”. The comfort reactions at the cabin aircrew station ranged from “not uncomfortable” to “a little uncomfortable”. The vector sum of the seat pan overall weighted X, Y, and Z accelerations (cruise flight APLN and CONV modes) were used to estimate the daily exposure duration thresholds for potential health risk (ISO 2631-1). During cruise APLN mode, the lowest duration thresholds occurred at the highest and lowest altitudes (10K ft MSL, 200K ft MSL); between 4 and 7 hours at the pilot and FE stations, and in 6 hours or greater at the cabin aircrew station. During cruise CONV mode, the lowest duration thresholds occurred with a 60-degree nacelle angle; between 2 and 4 hours at the pilot station, between 5 and 8 hours at the FE station, and between 7 and 16 hours at the cabin aircrew station. In summary, these results further support the substantial influence of operational vibration on the discomfort and pain associated with rotary-wing aircraft operations. The operation of the CV-22 is of particular concern with respect to the cockpit crew, where the potential for health risk can be reached in less than 8 hours of daily operation.					
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1.0 SUMMARY

This study characterized and assessed aircrew vibration exposure during operation of the CV-22 Osprey owned and operated by the AFSOC, 27th SOW, 20th SOS located at Cannon AFB, NW. The ISO 2631-1: 1997 (and amendment, 2010), the MIL-STD-1472H, and the American Conference of Governmental Industrial Hygienist (ACGIH) Threshold Limit Values (TLVs) for whole-body vibration were used as guidelines for the comfort and health risk assessments. The specific objectives of this study were:

1. Collect multi-axis acceleration data to characterize the vibration affecting the CV-22 aircrew during flight operations.
2. Assess the vibration exposures in accordance with existing human vibration guidelines and standards.
3. Expand the database of aircrew operational exposures residing in the 711 Human Performance Wing Collaborative Biomechanics Data Network (CBDN).

The study was funded by the DHP 6.2 Research, Development, Test, and Evaluation (RDT&E). The study was approved by the AFRL Institutional Review Board (IRB) as Not Human Subject Research (NHSR) (FWR20220094H).

Three portable battery-powered data acquisition units (DAUs) were used to collect accelerations at the pilot station (right side of cockpit), the flight engineer (FE) station (center cockpit), and at the aircrew station located in the forward cabin on the left side. It is noted that the cabin data was collected on a separate day as part of a second effort to characterize and assess cabin patient vibration. Triaxial accelerometer packs were attached to either the seat base, where feasible, or to a rigid seat support structure. Triaxial acceleration pads were placed on top of the seat pan and seat back cushions at all three stations. A triaxial accelerometer pack was also attached to the top of the pilot helmet. Data records were collected by aircraft task and the associated flight conditions, including ground operations, takeoff, hover flight, flight maneuvers in airplane (APLN) and conversion (CONV) modes, approach, and landing. The test conductor, located in the cabin area, triggered the (DAUs to collect 20 second records once the aircraft was on a targeted condition. The acceleration constant and proportional frequency bandwidth acceleration spectra were estimated at each station and measurement site. The overall unweighted and weighted (ISO 2631-1) accelerations were calculated between 1 and 80 Hertz (Hz) in the three orthogonal directions X (fore-and-aft), Y (lateral), and Z (vertical). For all records, the point vibration total values (pVTVs) at the seat pan and seat back were calculated as the vector sum of the overall weighted root-mean-square (rms) accelerations in the X, Y, and Z directions at these measurement sites. The vector sum of the seat pan and seat back pVTVs were then used to calculate the overall vibration total values (oVTVs) for assessing comfort reaction (ISO 2631-1). The vector sum of the seat pan overall weighted rms accelerations in the three directions, using the records collected during cruise flight (APLN and CONV modes), were used to estimate the exposure duration thresholds for potential health risk and likely health risk in accordance with the ISO 2631-1 Health Guidance Caution Zone (HGCZ).

During operations in APLN mode, the aircraft operates at 84% of the rotor revolutions per minute (RPM). Prominent multi-axis acceleration peaks occurred primarily at the blade passage frequency (BPF = 16.5 Hz) and at multiples of the BPF. During operations in CONV mode, the aircraft operates at 100% RPM. Prominent multi-axis acceleration peaks occurred at BPF = 20

Hz and at multiples of the BPF. In addition, vibration was also observed at frequencies below the BPF while in CONV mode.

Based on the *oVTVs*, pilot and FE comfort reactions primarily ranged from “a little uncomfortable” to “fairly uncomfortable”. The cabin aircrew comfort reactions primarily ranged from “not uncomfortable” to “a little uncomfortable”. Higher discomfort was associated with ground operations and landing.

During cruise in APLN mode, all three stations showed the lowest exposure duration thresholds (highest vibration) for potential health risk at the highest and lowest altitudes (10K feet (ft) Mean Sea Level (MSL) and 200 ft Above Ground Level (AGL)). At the pilot and FE stations, the duration thresholds associated with these altitudes would be reached between 4 and 7 hours of daily flight. At the cabin aircrew station, the duration thresholds would be reached in 6 hours or greater. During cruise in CONV mode, all stations showed lower exposure duration thresholds for potential health risk (higher vibration) with a nacelle angle of 60 degrees. The pilot station would reach the threshold in as little as 2 to 4 hours, at the FE station between 5 and 8 hours, and at the cabin aircrew station between 7 and 16 hours of daily flight. With a nacelle angle of 80 degrees, the pilot station would reach the threshold between 3 and 7 hours, at the FE station between 8 and 13 hours, and at the cabin aircrew station between 16 and 24 hours of daily flight.

In summary, these results further support the substantial influence of operational vibration on the discomfort and pain that has been associated with the operation of rotary-wing aircraft, particularly given the magnitudes of the higher frequency exposures that still result in the potential for health risk according to the standards and guidelines. The operation of the CV-22 is of particular concern with respect to the vibration exposures occurring in the cockpit, where the pilot and FE can be exposed to potential health risk in less than 8 hours of daily operation depending on the flight scenario.

2.0 INTRODUCTION

Epidemiological surveys have consistently reported that ~85 percent (%) 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 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. 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 effects, seat design, and validation testing are limited, perpetuating the health issues.

One major concern has been the limited amount of quality data for clearly characterizing the actual human multi-axis vibration exposure onboard 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). Guidelines can then be applied to these data for assessing the comfort and health risk associated with the exposures (ISO 2631-1: 1997; MIL-STD-1472H, 2020; ACGIH TLVs, 2023). Over recent years, several field studies have been conducted to quantify vibration exposure of military aircrew and have used these data to assess comfort and health risk. In 2007, aircrew vibration data were collected and assessed on the CV-22 at the request of the Air Force Flight Test Center, 412 Test Wing, to meet the objective of the Aircrew Systems Integration Test Plan for the CV-22 Engineering Manufacturing Development program, Crew Interface Vehicle Test Plan (Smith, 2008). The overall rating was marginal for both comfort and health risk. This was associated with the potential for health risk in as little as three hours of daily flight, as well as being considered “fairly uncomfortable” in accordance with ISO 2631-1. In 2013, the AFRL, the Army Public Health Center (APHC), and the National Guard Bureau (NGB) collaborated on the assessment of vibration exposure aboard the HH-60M Medevac and UH-72 Lakota located at the Vermont Army National Guard (VT ARNG) (Smith, Chervak, & Steinhauer, 2014). The health risk assessment suggested that certain aircrew aboard the HH-60M may be subjected to potential health risks in less than three hours of daily flight (Smith, Chervak, & Steinhauer, 2014). Between 2016 and 2020, The AFRL and APHC collaborated on a project to collect and assess aircrew vibration exposure aboard four rotary-wing aircraft, including the UH-60L Blackhawk (Smith, Chervak, & Clasing, 2018), MH-65D Dolphin (Smith & Chervak, 2019), CH47F Chinook (Smith & Chervak, 2020a), and the UH-1N Iroquois (Smith & Chervak, 2020b). The project was funded by the National Defense Center for Energy and Environment (NDCEE). The assessment of health risk showed that these aircrew were being exposed to the potential for health risk in less than eight hours of daily flight, even in as little as two hours of daily flight. These results emphasized the 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 vibration that is a major contributor to 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. Such

knowledge could lead to the development of more robust discomfort and pain mitigation strategies for the military. The AFRL 711 HPW/RH has used these field data to recreate the actual stressor environment in controlled laboratory studies for evaluating seat component influences and vibration mitigation design concepts, physiological responses associated with vibration, and aircrew task performance during simulated prolonged exposures.

The current CV-22 aircrew vibration study continues to expand our database of aircrew vibration exposures aboard rotary-wing/tilt-rotor aircraft. Many of the CV-22 flight test conditions evaluated back in 2007 were included in this study, with more emphasis on aircraft cruise APLN mode vs. cruise CONV mode, altitude, and the effects of the Active Vibration Suppression System (AVSS). In addition, back in 2007, the FE seat was directly attached to the cockpit door. In the current study, the FE seat was mounted on a rotating arm that is separate from the cockpit door. In 2007, the cabin aircrew member was seated on the right side of the cabin. In the current study the member was seated on the left side of the cabin.

The specific objectives of this study are to:

1. Collect multi-axis acceleration data to characterize the vibration affecting the aircrew onboard the CV-22 tilt-rotor aircraft.
2. Assess the comfort and health risk of the vibration exposures in accordance with existing human vibration guidelines and standards.
3. Enter the CV-22 acceleration data into the AFRL 711 HPW/RH CBDN, which can be accessed via a Department of Defense (DoD) Common Access Card (CAC).

3.0 METHODS AND PROCEDURES

3.1 Aircraft and Measurement Locations

The CV-22 aircraft used in this study is owned and operated by the 20th SOS located at Cannon AFB, NM. Two flight tests were conducted. One flight test focused on measuring the vibration exposure of the aircrew and targeted the pilot and FE stations in the cockpit. A seated occupant located in the rear cabin on the left side was also targeted for data collection. However, all data collected at this site was corrupted and not included in this report. The other flight focused on measuring the vibration exposure of patients during emergency medical transport and targeted one seated patient in the cabin and two supine litter patients in the cabin area. Both flight tests included the same flight conditions (see Section 3.3). While this technical report addresses aircrew vibration, data collected on the seated cabin patient were used to assess aircrew comfort and health risk and included in this report. A separate technical report will address patient vibration aboard the CV-22. During both flights, the test conductor was located in the forward cabin seat.

3.2 Equipment, Instrumentation, and Measurement Sites

The Remote Vibration Environment Recorder (REVER), developed by the AFRL Human Effectiveness Directorate (711 HPW/RH), was used to collect multi-axis vibration data at the aircrew stations. Each REVER, illustrated in Figure 1, consists of the following:

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

Three REVERs were used; one for each targeted station. 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 adhesive tape was used to secure the pack to the appropriate site. Triaxial accelerometer pads were used to measure the vibration transmitted to the seated 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 and measurement sites targeted for data collection, including the type of instrumentation.

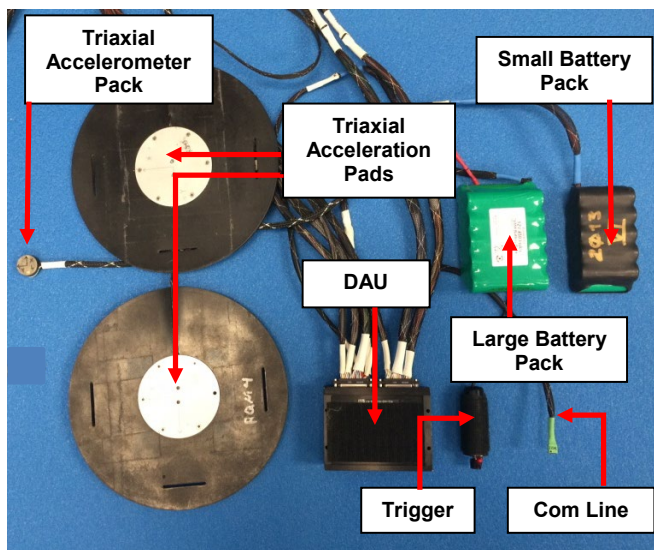
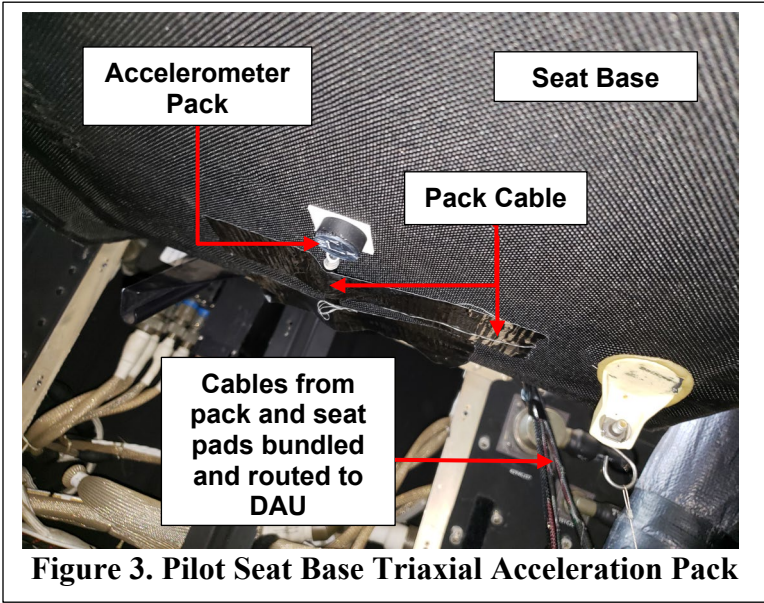
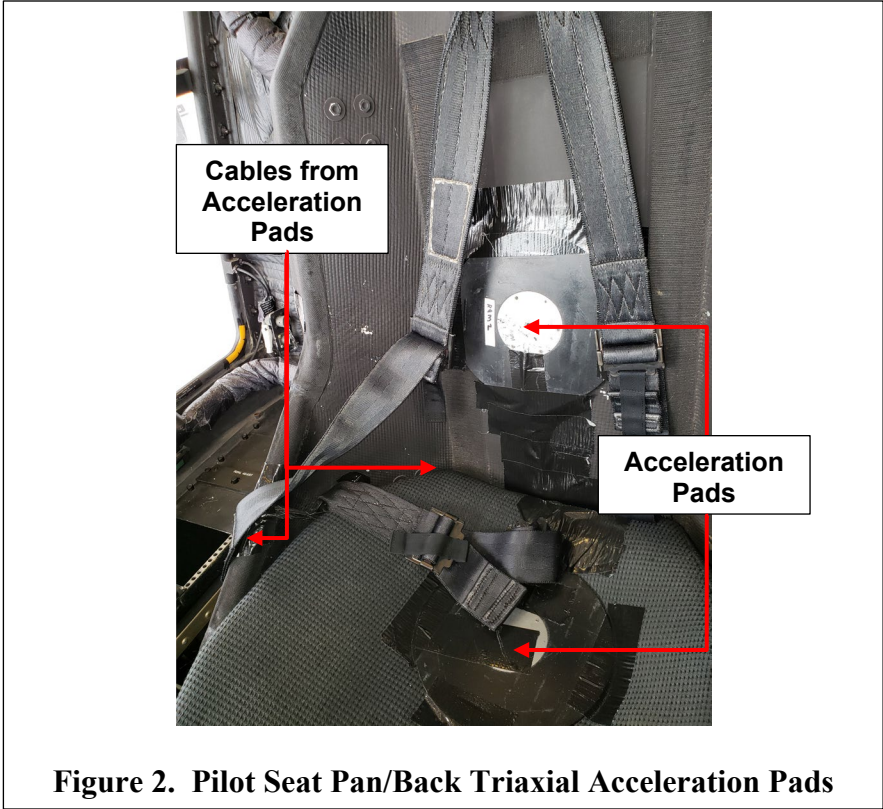


Figure 1. Remote Vibration Environment Recorder (REVER)

Table 1. CV-22 Stations/Locations, Measurement Sites, and Type of Sensors

Station	Measurement Site	Instrumentation
Pilot Station (Right Side Cockpit)	Seat Base	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
	Helmet	Triaxial Accelerometer Pack
Flight Engineer Station (Center Cockpit)	Seat Support Rail	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
Aircrew Station (Forward Left Cabin – facing sideways)	Rigid Metal Bar	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad

At the pilot station, the acceleration pads were attached to the seat pan and seat back as shown in Figure 2. An accelerometer pack was attached beneath the seat onto the seat base as shown in Figure 3. An accelerometer pack was attached to the top of the pilot helmet as shown in Figure 4.



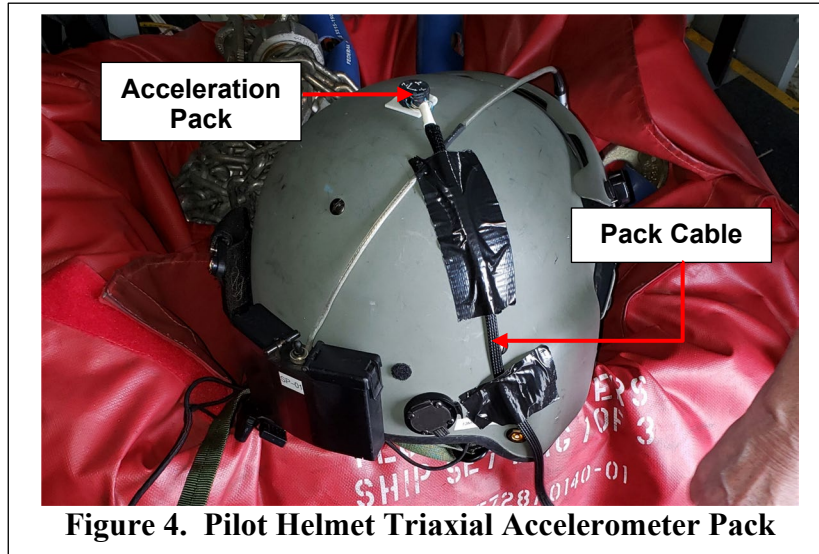


Figure 4. Pilot Helmet Triaxial Accelerometer Pack

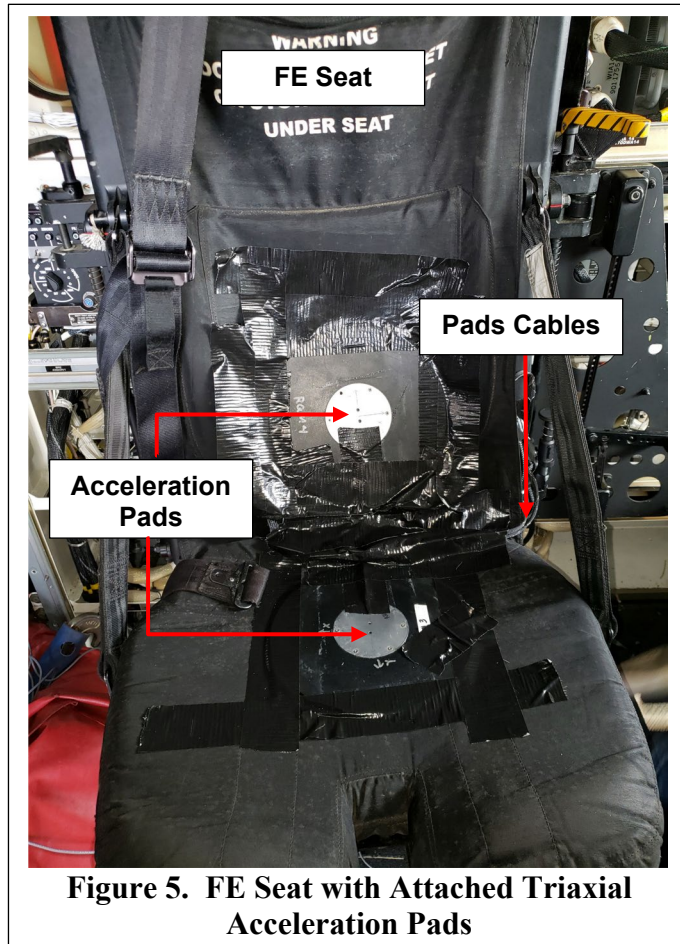
The DAU and battery packs were secured to the floor on the right side of the pilot seat. All seat sensor cables were routed to the DAU channel cables and secured as necessary to avoid any snags. The connection of the helmet cable to the DAU cable were made via breakaway connectors. This allowed the pilot to disconnect the helmet and communication cables and safely exist the cockpit in the case of an emergency.

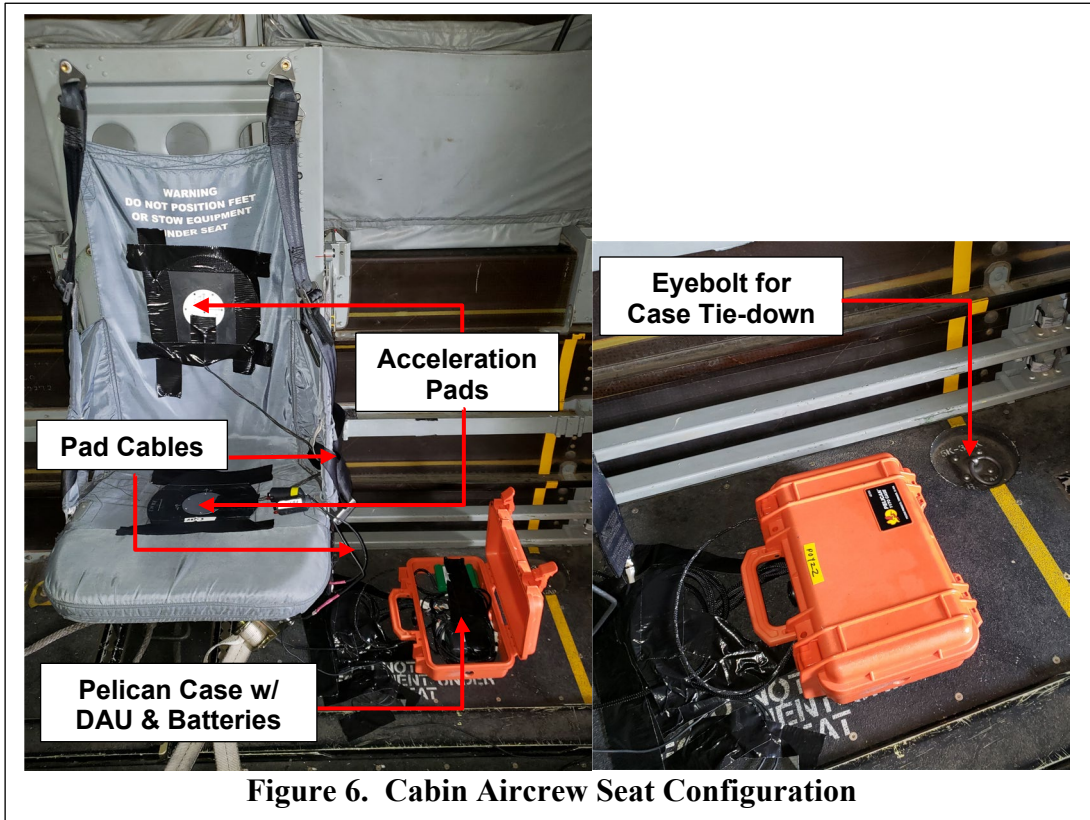
At the FE station, the acceleration pads were attached to the seat pan and seat back as shown in Figure 5. The triaxial accelerometer pack was mounted onto the rigid metal horizontal seat support bar located behind the seat back.

Trigger cables from the two cockpit DAUs were routed beneath the cockpit door to the forward left cabin seat.

At the cabin aircrew station, the acceleration pads were attached to the seat pan and seat back as shown in Figure 6. The triaxial accelerometer pack was mounted onto the rigid metal seat support bar that ran along the aircraft sidewall. The DAU and battery packs were located in a small Pelican case secured to the floor to the left of the seat (Figure 6). All seat sensor cables were routed to the DAU via port holes drilled into the case.

A trigger device (Figure 1) was attached to each of the three cables routed from the DAUs to the forward left cabin seat. This seat was occupied by the test conductor (also cabin aircrew station) who was 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 via the communication cable (Com Line, Figure 1). 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.





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 conditions listed in Table 2. The flight conditions were organized relative to specific flight tasks. The test conductor triggered data collection for the three targeted stations once the pilot or copilot indicated that the aircraft was on the flight condition. Multiple data records were collected for several of the conditions as annotated in Table 2 for each of the three aircrew stations. Data records were collected throughout the flight and not necessarily collected in the order presented in Table 2. The test conductor assured that the data records were numbered consecutively in the order they were collected. A total of 187 to 224 records were collected at each aircrew station.

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.

3.3.2 Data Processing and Analysis

For assessing comfort, the equations presented in this section use the nomenclature provided in the current version of ISO 2631-1 (1997), and include the seat pan and seat back $pVTV$ s and the $oVTV$. For assessing health risk, the equations presented in this section use the nomenclature provided in the current version of the ACGIH TLV for Whole-Body Vibration (2023), and include the overall seat pan weighted rms acceleration and the vector sum of the daily overall

Table 2. CV-22 Flight Tasks and Flight Condition Records

Task/Condition	# of Records		
	PI	FE	AC
TASK: GROUND OPERATIONS			
Ground Taxi	3	2	7
TASK: TAKEOFF MANEUVERS			
Normal Takeoff	4	4	3
Short Takeoff	1	1	3
60 Degree RTO	2	2	-
Climb Conversion Mode	6	6	-
Climb Airplane Mode	3	3	4
TASK: CRUISE AIRPLANE (APLN) MODE			
10K Ft MSL	8	8	10
10K Ft MSL AVSS Off	8	8	10
7K Ft MSL	8	8	10
7K Ft MSL AVSS Off	8	8	10
5K Ft MSL	9	9	10
5K Ft MSL AVSS Off	8	8	10
200 Ft AGL	8	8	10
200 Ft AGL AVSS Off	8	8	9
TASK: CRUISE CONVERSION (CONV) MODE			
500 Ft AGL 80 Degrees	8	8	10
500 Ft AGL 80 Degrees AVSS Off	8	8	9
500 Ft AGL 60 Degrees	8	8	10
500 Ft AGL 60 Degrees AVSS Off	8	8	9
200 Ft AGL 80 Degrees	8	8	10
200 Ft AGL 80 Degrees AVSS Off	8	8	9
200 Ft AGL 60 Degrees	8	8	10
200 Ft AGL 60 Degrees AVSS Off	9	9	9
TASK: APPROACHES AND HOVERING FLIGHT			
Approach OGE Hover	4	4	4
OGE Hover	11	11	12
Approach IGE Hover	4	4	4
IGE Hover	6	6	12
TASK: DESCENT AND LANDING			
Descent	6	6	6
Landing from Hover	5	5	11
Roll on Landing	3	3	3
TOTAL RECORDS	188	187	224
PI: Pilot FE: Flight Engineer AC: Cabin Aircrew MSL: Mean Sea Level AGL: Above Ground Level		AVSS: Active Vibration Suppression System IGE: In Ground Effect OGE: Out of Ground Effect RTO: Running Takeoff	

seat pan weighted rms accelerations in the X, Y, and Z directions for assessing health risk. The numerical quantities calculated for assessing comfort and health risk align with the guidelines presented in ISO 2631-1: 1997.

A computer program developed by the 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 rms acceleration spectra were calculated from the power spectral densities in 0.5 Hz intervals. The constant bandwidth rms acceleration spectra were used to identify the frequency location of peak accelerations.

Each acceleration time history record 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 comfort and health risk of the exposures in accordance with the current guidelines and standards.

For each 20-s data record, the overall unweighted rms acceleration level, a_l , was calculated between 1 and 80 Hz at the seat base or seat support bar/rail, seat pan, seat back, and helmet (pilot only) using the unweighted one-third octave rms acceleration spectra in each of the three orthogonal axes l (X, Y, and Z):

$$a_l = [\sum_i a_{li}^2]^{1/2} \quad (1)$$

where a_{li} is the unweighted rms acceleration associated with direction l for the i th one-third octave frequency component.

The overall weighted rms acceleration, a_{wl} , was calculated between 1 and 80 Hz at the seat pan and seat base using the weighted one-third octave rms acceleration spectra in each axis l (X, Y, and Z):

$$a_{wl} = k_l (\sum_i [W_{li} a_{li}]^2)^{1/2} \quad (2)$$

where W_{li} is the frequency weighting associated with direction l for the specific measurement site (seat pan or seat back) for the i th one-third octave center frequency component, and k_l is the multiplying factor associated with direction l for the specific measurement site and assessment (comfort reaction or health risk).

For assessing comfort, the seat pan and seat back $pVTV$ s (ISO 2631-1: 1997) were calculated as the vector sum of the overall weighted rms accelerations in the three directions, using k values for comfort, for each flight condition and the associated records:

$$pVTV = [a_{wx}^2 + a_{wy}^2 + a_{wz}^2]^{1/2} . \quad (3)$$

The $oVTV$ s (ISO 2631-1: 1997) were calculated as the vector sum of the seat pan and seat back $pVTV$ s. The seat pan and seat back $pVTV$ s, and the $oVTV$ s for each record were compared to the

weighted accelerations associated with the comfort reactions given in ISO 2631-1: 1997, Annex C. It is noted that, if the seat back data are not available, the seat pan $pVTV$ calculated using the multiplying factors associated with health risk can be used. The comfort reactions include “Not Uncomfortable”, “A Little Uncomfortable”, “Fairly Uncomfortable”, “Uncomfortable”, “Very Uncomfortable”, and “Extremely Uncomfortable”.

For assessing health risk during operation of the CV-22, it was assumed that the seat pan data records collected during cruise APLN mode and cruise CONV mode (Table 2) were representative of the range of exposures experienced by the aircrew on a daily basis. Therefore, for each seat pan record,

$$a_{wl,daily} = a_{wl} \quad (4)$$

where $a_{wl,daily}$ is the daily overall weighted rms acceleration in the l direction for the expected daily exposure duration (ACGIH 2023) associated with each record, and a_{wl} is calculated using the k values associated with health risk (ISO 2631-1). The vector sum is now defined as

$$a_{v,daily} = \left([a_{wx,daily}^2] + [a_{wy,daily}^2] + [a_{wz,daily}^2] \right)^{\frac{1}{2}}. \quad (5)$$

The ISO HGCZ illustrated in Figure 7 (redrawn from ISO 2631-1: 1997 Annex B) was used to assess health risk. Note that the vertical axis represents the vector sum of the daily overall weighted rms accelerations or $a_{v,daily}$ from Equation (5). The horizontal axis represents the expected daily exposure duration. For vector sum accelerations falling below the lower

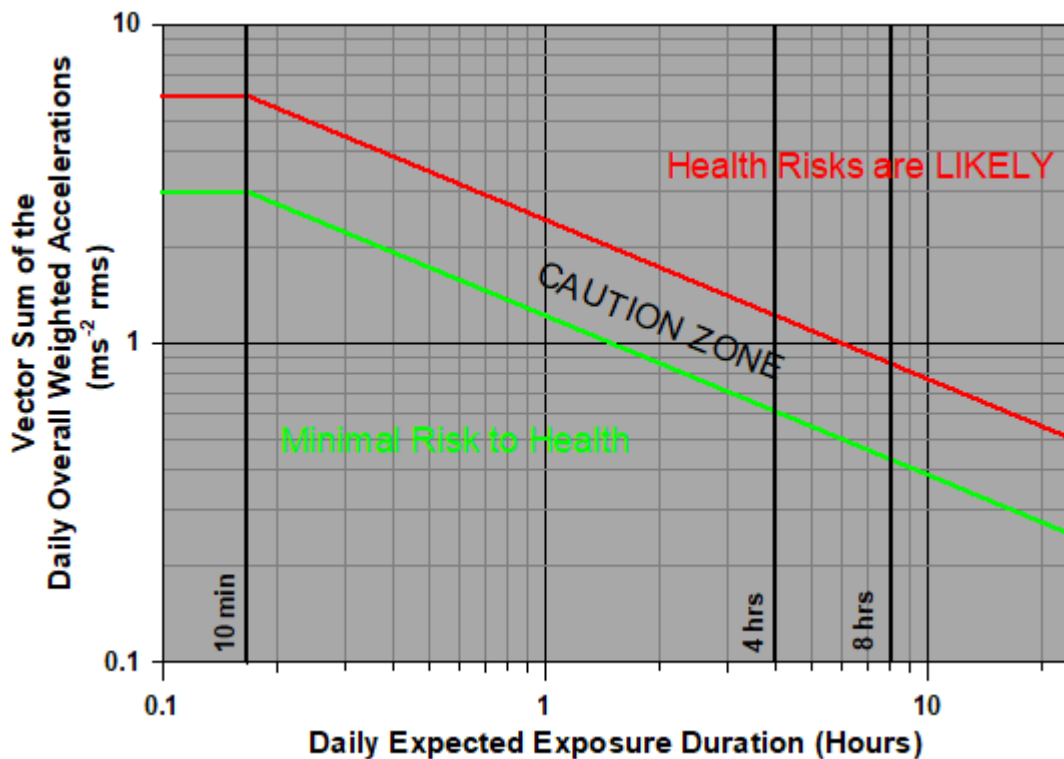


Figure 7. ISO 2631-1 Health Guidance Caution Zones (HGCZs)

boundary (green) of the ISO HGCZ for the expected daily exposure duration, health risks are unlikely or considered minimal. 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 (red), health risks are likely for repeated occupational exposures. Both the MIL-STD-1472H and ACGIH TLV state that daily seated exposures shall not fall within the zone “Health Risks Likely”, and attempts shall be made to reduce the exposure magnitude or duration of those exposures falling within the “Caution Zone” (potential health risk) to the “Health Risks Unlikely” zone.

One major difficulty associated with military aircraft operations is that the daily vibration exposure durations can vary from day to day, week to week, etc., depending on the particular mission, and therefore influence the daily health risk outcome. The representative vibration levels measured aboard the CV-22 were used to gauge the range of daily exposure duration thresholds for potential health risk (lower green boundary) and the range of daily exposure duration thresholds for likely health risk (upper red boundary) based on the ISO 2631-1 HGCZ shown in Figure 7. Using the seat pan $a_{v,daily}$ calculated for each cruise APLN mode and cruise CONV mode record, the exposure duration threshold for potential health risk was calculated as:

$$T = \frac{(1.5)}{a_{v,daily}^2} \quad (4)$$

Any daily exposure durations exceeding T in Equation (4) would indicate the potential for health risk. Likewise, the exposure duration threshold for likely health risk was calculated as:

$$T = \frac{(6.0)}{a_{v,daily}^2} \quad (5)$$

Any daily exposure durations exceeding T in Equation (5) would indicate that health risks are likely.

4.0 RESULTS

All Figures and Tables referred to in this section are located in the Appendix.

4.1 Spectral Characteristics of the Multi-Axis Accelerations Onboard the CV-22

Rotary-wing and tilt-rotor aircraft generate persistent vibration caused by the propulsion system at frequencies associated with the rotor speed. For the purpose of this report, the frequency associated with the rotor speed is referred to as the propeller rotation frequency (PRF). A peak is typically expected to occur at the blade passage frequency (BPF), which is predicted as the number of blades multiplied by the PRF. Additional peaks are also expected at multiples of the BPF. The BPF peak may or may not be the highest in magnitude depending on the aircraft and flight condition. The PRF and BPF may vary slightly depending on the flight maneuver and whether the aircraft is operated at 100% power. The CV-22 can operate in two modes: APLN mode and CONV mode. In addition, in CONV mode, the aircraft nacelle can be oriented at different angles (see Table 2). In APLN mode, the aircraft typically operates at approximately 84% RPM. In CONV mode, the aircraft typically operates at 100% RPM. In some cases, the aircraft operates at 103.5% RPM. Table 3 lists these values and their associated spectral components in cycles per second or Hz. Section 4.1.1 summarizes the spectral characteristics associated with APLN mode at the three stations. Section 4.1.2 summarizes the spectral characteristics associated with CONV mode at the three stations.

Table 3. CV-22 Propulsion Frequency Spectra Components

%RPM	SPECTRA COMPONENT (Hz)					
	1P (PRF*)	2P	3P (BPF**)	6P	9P	12P
84	5.6	11.1	16.7	33.3	50.0	66.7
100	6.6	13.2	19.8	39.7	59.6	79.4
103.5	6.9	13.7	20.6	41.2	61.8	82.4

*PRF = Propeller Rotation Frequency, **BPF = Blade Passage Frequency
 Note: These are approximate values based on 100% RPM = 397 revolutions per minute

4.1.1 APLN Mode Spectra

Figure A-1 illustrates an example of the CV-22 unweighted acceleration spectra occurring during cruise flight in APLN mode (10K ft MSL) at the pilot seat pan, seat back, and helmet in the fore-and-aft (X), lateral (Y), and vertical (Z) directions with the AVSS ON and AVSS OFF. With both the AVSS ON and AVSS OFF, any peaks observed below 10 Hz were relatively small, the higher peaks occurring below the PRF. It is expected that these peaks may be contributed to by other factors including air buffeting or turbulence, and even occupant voluntary movement. A distinct peak was observed at 16.5 Hz in all three directions that does correspond to the BPF in APLN mode (Table 3, data processed in 0.5 Hz increments). Additional peaks were also observed at multiples of the BPF. At the pilot helmet, the highest peak occurred in the vertical

(Z) direction. As expected, the helmet vibration was damped beyond the BPF. With emphasis on the vertical (Z) vibration, Figure A-1 does show that, at the pilot station, the AVSS ON was associated with lower vertical (Z) vibration at the BPF at the occupant/seat interfaces but not necessarily at the helmet, where the BPF peak was similar to or higher than that occurring with the AVSS OFF.

Figure A-2 illustrates an example of the CV-22 unweighted acceleration spectra occurring during cruise flight in APLN mode (10K ft MSL) at the FE seat pan and seat back in the fore-and-aft (X), lateral (Y), and vertical (Z) directions with the AVSS ON and AVSS OFF. As with the pilot station, any peaks observed below 10 Hz were relatively small; the higher peaks occurring below the PRF. Distinct multi-axis peaks were observed at 16.5 Hz and associated with the BPF, with additional peaks occurring at multiples of the BPF. The AVSS ON tended to be associated with lower FE vertical (Z) vibration at the BPF at the occupant/seat interface. For the examples shown in Figure A-2, the mitigation of the FE vertical BPF peak with the AVSS ON was not as dramatic as observed at the pilot station.

Figure A-3 illustrates an example of the CV-22 unweighted acceleration spectra occurring during cruise flight in APLN mode (10K ft MSL) at the forward cabin aircrew seat. Again, distinct multi-axis peaks were observed at 16.5 Hz (BPF) with additional peaks occurring at multiples of the BPF. However, in contrast to the results at the cockpit stations, the vertical (Z) BPF peak is notably reduced with the AVSS OFF. This station did show more distinct but relatively low peaks associated with the PRF around 5.5 Hz (Table 3).

Additional observations regarding the effects of altitude, vibration direction, nacelle angle, and AVSS status are addressed in subsequent sections of this report.

4.1.2 CONV Mode Spectra

Figure A-4 illustrates an example of the CV-22 unweighted pilot seat pan acceleration spectra occurring during cruise flight in CONV mode (500 ft AGL) at the two tested nacelle angles with the AVSS ON and AVSS OFF. In CONV mode, there did appear to be more substantial lower frequency vibration, particularly between 9 and 13 Hz, as compared to APLN mode. While the lower frequency vibration may be associated with the PRF and multiples of the PRF, there may be other contributing factors. The highest peak in this lower frequency range was observed at around 11.5 Hz in the lateral (Y) direction (Figure A-4) and may be associated with a multiple of the PRF (2P, Table 3). At 500 ft AGL and a nacelle angle of 80 degrees, the 20 Hz BPF peak was associated with 100% RPM (Table 3). A distinct peak was also observed at 40 Hz or at 2xBPF. Variable results were observed at 40 Hz. For this flight test condition, it doesn't appear that the AVSS status had much effect on the vertical (Z) BPF peak. At 500 ft AGL and a nacelle angle of 60 degrees, there appeared to be two distinct peaks at 20 Hz (BPF at 100% RPM) and between 17-18 Hz. The two peaks may be due to fluctuating rotor speed during the data collection. In addition, with the 60 degrees nacelle angle, the lower frequency vibration appeared to be higher as compared to 80 degrees. With the AVSS ON, the vertical (Z) BPF peak at 20 Hz appeared to be damped as compared to AVSS OFF.

Figure A-5 illustrates an example of the CV-22 unweighted FE seat pan acceleration spectra occurring during cruise flight in CONV mode (500 ft AGL) at the two tested nacelle angles.

Similar peak characteristics were observed at the FE station as were observed at the pilot station, including the substantial lower frequency vibration particularly observed between 9 and 13 Hz. The highest peak in this lower frequency range was observed at around 11.5 Hz in the lateral (Y) direction (Figure A-5). At 500 ft AGL and a nacelle angle of 80 degrees, the BPF peak was observed at 20 Hz and associated with 100% RPM. There appeared to be little effect of the AVSS on the vertical (Z) peak at the BPF. At 500 ft AGL and a nacelle angle of 60 degrees, two distinct peaks were observed; one at 20 Hz and the other between 17-18 Hz. As with the pilot station, with the 60 degrees nacelle angle, the lower frequency vibration appeared to be higher as compared to 80 degrees. With the AVSS ON, the vertical (Z) peak at 20 Hz appeared to be damped as compared to AVSS OFF.

Figure A-6 illustrates an example of the CV-22 unweighted cabin aircrew acceleration spectra occurring during cruise flight in CONV mode (500 ft AGL) at the two tested nacelle angles. While this station did not show the substantial lower frequency vibration, peaks were observed in the vicinity of 6.5 Hz which were associated with the PRF when operating at 100% RPM (Table 3), for both nacelle angles. At 500 ft AGL and nacelle angle of 80 degrees, peaks were observed at 20 Hz (BPF) and at 40 Hz (2xBPF). As shown in Figure A-6, at 500 ft AGL and a nacelle angle of 60 degrees, peaks associated with the BPF and 2xBPF were not easily observed. The AVSS did not appear to have any notable effect on the vertical (Z) peaks.

Additional observations regarding the effects of altitude, vibration direction, nacelle angle, and AVSS status are addressed in subsequent sections of this report.

4.2 Overall Unweighted Accelerations

Figures A-7 – A-9 illustrate the mean overall unweighted accelerations \pm one standard deviation for all tasks and flight conditions at the pilot station, FE station, and cabin aircrew station, respectively. Tables A-2 – A-4 list the overall unweighted seat pan accelerations in each direction l , a_l , during cruise APLN mode for all four altitudes with the AVSS ON at each station, respectively. The means \pm one standard deviation are included. It is cautioned that the summary provided below on the overall unweighted accelerations are observations and have not been statistically evaluated for significant effects of measurement site and direction.

At the pilot station (Figure A-7) during cruise APLN mode, similar overall unweighted accelerations tended to occur among the three directions at the lower altitudes with the AVSS ON. This is shown in the unweighted seat pan data listed in Table A-2. Figure A-7 and Table A-2 do show that the highest overall unweighted vibration levels occurred at 10K ft MSL in both the fore-and-aft (X) and vertical (Z) directions at the three pilot measurement sites (seat base, seat pan, seat back). As illustrated in Figure A-7, higher overall unweighted vertical (Z) acceleration levels occurred in cruise APLN mode at all four altitudes with the AVSS OFF. This coincides with the spectral observations illustrated in Figure A-1 for the seat pan and seat back, particularly at the BPF in APLN mode (16.5 Hz). At the pilot station during cruise CONV mode, all three measurement sites tended to show higher overall unweighted accelerations in all three directions with a nacelle angle of 60 degrees, regardless of altitude and AVSS status (Figure A-7). There did not appear to be any noticeable effect of altitude and no effective influence of the AVSS.

At the FE station (Figure A-8) during cruise APLN mode, the highest overall unweighted acceleration tended to occur in the lateral (Y) direction, particularly at the seat pan. These higher lateral (Y) unweighted seat pan levels are reflected in Table A-3 at all four altitudes. While there was a tendency for higher overall unweighted levels of vertical (Z) vibration in cruise APLN mode with the AVSS OFF, this was not consistent across the tested altitudes. Figure A-2 does suggest that the BPF peak (16.5 Hz) was higher with the AVSS OFF at 10K ft MSL. This appeared not to have influenced the overall unweighted acceleration levels. There appeared to be less effect of altitude on the unweighted vibration levels at the FE station (Figure A-8 and Table A-3). At the FE station during cruise CONV mode, the seat base and seat pan showed higher overall unweighted accelerations in all three directions with a nacelle angle of 60 degrees. At the seat back, this observation primarily occurred in the lateral (Y) and vertical (Z) directions. During cruise CONV mode, the overall unweighted acceleration levels did not appear to be effectively influenced by the AVSS status.

At the cabin aircrew station (Figure A-9) during cruise APLN mode, the highest overall acceleration was quite notable in the fore-and-aft (X) direction, relative to the side-seated aircrew (lateral (Y) direction relative to aircraft). These higher fore-and-aft (X) levels at the seat pan are shown in Table A-4. While the overall vertical (Z) vibration tended to be the highest at 10 K ft MSL, the fore-and-aft (X) vibration showed higher levels at the lower altitudes, particularly at the seat pan, as shown in Table A-4. In contrast to the cockpit stations, there was a tendency for the overall vertical (Z) unweighted acceleration levels to be lower with the AVSS off at the cabin aircrew station, particular at the higher altitudes (Figure A-9). At the cabin aircrew station during cruise CONV mode, the highest overall unweighted levels were observed in the fore-and-aft (X) direction of the side-seated aircrew with no clear effect of altitude or AVSS status. There appeared to be some minimal effect of the nacelle angle on the overall unweighted acceleration levels, with higher lateral (Y) and vertical (Z) levels observed at the 60-degree nacelle angle.

4.3 Assessment of the CV-22 Aircrew Comfort Reaction and Health Risks

4.3.1 Overall Weighted Accelerations

Tables A-2 – A-4 include the daily overall weighted seat pan accelerations in each direction l , $a_{wl,daily}$, during cruise APLN mode for all four altitudes with the AVSS ON. The means \pm one standard deviation are included. Tables A-2 – A-4 show the substantial reduction in acceleration as a result of the frequency weightings. In addition, the tables show that, regardless of the relative overall unweighted accelerations, the daily overall weighted seat pan vertical (Z) accelerations, $a_{wz,daily}$, were the highest at all three stations. Although not shown, the overall weighted seat back fore-and-aft (X) accelerations, a_{wx} , were the highest at all three stations. 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.

4.3.2 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. Figures A-10 – A-12 illustrated the $pVTV$ s at the seat pan and seat back, and the $oVTV$ associated with each flight condition. It is noted that, at the aircrew cabin station, the seat back $pVTV$ and the

$oVTV$ could not be calculated due to the corrupt measurements observed for Seat Back Y (see Figure A-9). The ISO 2631-1 does recommend that, if horizontal seat back data are not available, the horizontal vibration at the seat pan should be multiplied by $k = 1.4$ instead of 1. This results in the comfort assessment using the seat pan $pVTV$ for health at this station. The figures include color-coded bands associated with each comfort reaction. The Comfort Reactions are independent of time.

At the pilot station, Figure A-10 shows that the lower seat back $pVTV$ s did not have much influence on the $oVTV$, given the similarities in magnitude to the seat pan $pVTV$ s. The $oVTV$ s indicated that the CV-22 vibration at the pilot station would range from being considered “a little uncomfortable” to “fairly uncomfortable”, depending on the flight condition. There appeared to be somewhat higher $oVTV$ s associated with the highest (10K ft MSL) and lowest (200 ft AGL) altitudes. During cruise APLN mode, higher discomfort was associated with the AVSS OFF condition at all altitudes. During cruise CONV mode, the most discomfort was associated with a nacelle angle of 60 degrees (based on the $oVTV$ s).

At the FE station, Figure A-11 also shows the lower seat back $pVTV$ s and similar seat pan $pVTV$ s and $oVTV$ s as observed at the pilot station. The $oVTV$ s indicated that the CV-22 vibration at the FE station would be mostly considered “a little uncomfortable” with some instances of being considered “fairly uncomfortable” depending on the flight condition. During cruise APLN mode, the data indicated that higher discomfort may occur with the AVSS OFF at certain altitudes. During cruise CONF mode, the data suggested higher discomfort with a nacelle angle of 60 degrees.

At the aircrew cabin station, Figure A-12 shows that most of the CV-22 vibration would be considered to range from “not uncomfortable” to “a little uncomfortable”, with higher discomfort associated with ground operations and landing. There appeared to be slightly more discomfort associated with a nacelle angle of 60 degrees.

4.3.3 Aircrew Vibration Health Risk Assessment (ISO 2631-1)

As described in Section 3.3.2, the cruise flight APLN mode and CONV mode seat pan data were used to gauge the daily exposure duration thresholds for potential health risk and likely health risk. As observed in the $pVTV$ s and $oVTV$ s illustrated for the flight conditions in Figures A-10 – A-12, the vibration levels associated with cruise flight were representative of the vibration associated with the operation of the CV-22, and the assumption was made that this would be true regardless of the mission. This is also based on the assumption of no adverse weather (such as high wind) or evasive maneuvering (such as may occur when under live fire).

Figure A-13 illustrates the range of exposure duration thresholds associated with potential health risk based on the vector sum of the daily overall weighted rms accelerations, $a_{v,daily}$, calculated for each record collected at each altitude during cruise APLN mode and for each record collected at the two altitudes and two nacelle angles during cruise CONV mode. The AVSS status was AVSS ON. Note that the Y-axis is plotted with respect to a log scale. Tables A-2 – A-4 list $a_{wl,daily}$ at the seat pan in each direction l for each record, and the $a_{v,daily}$ for each record. The duration thresholds for potential health risk and likely health risk, based on using the highest overall weighted seat pan acceleration (Section 4.2.1; highest weighted values occurred in vertical (Z) axis, $a_{wz,daily}$), as well as the seat pan $a_{v,daily}$ in Equations (4) and (5), are included in the tables. Thresholds of less than 8 hours are shown in yellow.

In APLN mode, all three stations showed the lowest daily exposure duration thresholds (highest overall weighted accelerations) at the highest (10 K ft MSL) and lowest altitudes (200 ft AGL). For the pilot and FE in the cockpit, these thresholds were reached in 4 to 7 hours of daily exposure based on the $a_{v,daily}$ (Figure A-13 and Tables A-2, A-3). For the cabin aircrew station, these thresholds were reached in approximately 6 hours or greater based on the $a_{v,daily}$. In CONV mode, Figure A-13 illustrates the lower exposure duration thresholds associated with a nacelle angle of 60 degrees (higher overall weighted vibration levels). At the pilot station, the duration thresholds associated with a nacelle angle of 80 degrees fell primarily between 3 and 7 hours, with one record showing a threshold of just over 8 hours. The duration thresholds associated with a nacelle angle of 60 degrees fell between 2 and 4 hours. At the FE station, the duration thresholds associated with a nacelle angle of 80 degrees fell between 8 and 13 hours. The duration thresholds associated with a nacelle angle of 60 degrees fell between 5 and 8 hours. At the cabin aircrew station, the duration thresholds associated with a nacelle angle of 80 degrees fell between 16 and 24 hours. The duration thresholds associated with a nacelle angle of 60 degrees fell between 7 and 16 hours.

4.4 Comparison of 2007 and Current CV-22 Aircrew Vibration Data

Figure A-14 illustrates the 2007 and current study aircrew seat pan $a_{v,daily}$ values for each record collected during cruise APLN mode and cruise CONV mode with the AVSS ON and AVSS OFF (current study only). Included in the figure are color-coded bands representing the associated daily exposure duration thresholds for potential health risk (ISO 2631-1). The current study included the addition of data collected in APLN mode at 200 ft AGL. The 2007 study only included cruise in CONV mode with a nacelle angle of 60 degrees. Interestingly, the $a_{v,daily}$ values occurring during cruise APLN mode with the AVSS ON in the 2007 study were more similar to the $a_{v,daily}$ values occurring during cruise APLN mode with the AVSS OFF in the current study, with the pilot vibration levels being the highest and associated with daily exposure duration thresholds for potential health risk occurring in 2 to 4 hours. The current study shows more similarity in the vibration levels among the stations with the AVSS ON, particularly at the cockpit stations. Figure A-13 delineates these similarities among the four altitudes. In general, the $a_{v,daily}$ values during cruise CONV mode were similar, regardless of the AVSS status. The data did suggest that the 2007 cabin aircrew $a_{v,daily}$ values occurring during cruise CONV mode were somewhat higher as compared to the currently study and, therefore, associated with lower exposure duration thresholds. The same individual occupied the cabin aircrew station in both studies; seated on the right side in the 2007 study and on the left side in the current study.

Figure A-14 also illustrates the effect of the AVSS status on the daily overall weighted seat pan accelerations and the associated daily exposure duration thresholds during cruise APLN mode in the current study. At the pilot station, the exposure duration thresholds were notably higher with the AVSS ON, reaching 4 hours and even beyond 8 hours across the altitudes. The thresholds with the AVSS OFF ranged between about 2 and 4 hours across the altitudes. At the FE station, there appears to be a tendency for higher thresholds with the AVSS ON, reaching values above 8 hours, while the AVSS OFF showed thresholds primarily between 4 and 8 hours. In contrast, at the cabin aircrew station, the exposure duration thresholds fell between 4 and 8 hours across the altitudes with the AVSS ON, but all thresholds fell above 8 hours with the AVSS OFF.

5.0 DISCUSSION AND CONCLUSIONS

This document provides a summary of the vibration exposure characterization and assessment conducted onboard the CV-22 tilt-rotor aircraft. The characteristics of the spectra generated by the CV-22 were similar to that observed during other investigations conducted on rotary-wing and tilt-rotor aircraft, where peak accelerations were associated with the propulsion system and occurred at relatively distinct frequencies. The CV-22 has the unique capability to fly in APLN mode as well as CONV mode, which is more similar to a helicopter. As shown in the previous 2007 study, the aircraft operates at 84% RPM in APLN mode, which generate a BPF peak at around 16.5 Hz and at multiples of the BPF. The aircraft operates at 100% RPM in CONV mode, which generate a BPF peak at around 20 Hz and at multiples of the BPF. These vibration frequencies can be felt by the aircrew.

As shown in the overall unweighted rms accelerations, the vibration transmitted to the aircrew at the seat pan and seat back were multi-axis, where the highest vibration did not necessarily occur in the vertical (Z) direction. However, the ISO 2631-1 frequency weightings and multiply factors, based on psychophysical and biodynamic responses, resulted in weighted values where the highest overall seat pan weighted rms acceleration consistently occurred in the vertical (Z) direction, while the highest overall seat back weighted rms acceleration typically occurs in the fore-and-aft (X) direction. This was particularly noteworthy at the cabin aircrew station during cruise APLN mode, where the overall unweighted fore-and-aft (X) seat pan accelerations were substantially higher as compared to the levels occurring in the other directions (Figure A-9), as well as compared to the levels observed at the cockpit stations. This was most likely affected by the attachment of the seat to the fuselage, the attachment of the wings over the cabin, and that the aircrew were seated very near the plane of the rotating propellers. Regardless, the highest overall weighted seat pan accelerations still occurred in the vertical (Z) direction (not shown). These observations have also been noted among other rotary-wing aircraft. These findings, in combination with the frequency characteristics, provide valuable input for developing effective mitigation strategies.

The CV-22 is equipped with the AVSS, which is typically flown in the ON status. The concept is focused on mitigating vertical (Z) vibration. At the request of the aircrew, data were collected for both modes with the AVSS ON and the AVSS OFF. The most notable effect occurred at the pilot station during cruise APLN mode, where the highest overall unweighted vertical (Z) seat pan accelerations occurred as compared to the other stations with the AVSS OFF. With the AVSS ON, both the pilot station unweighted and weighted seat pan vertical (Z) accelerations were substantially damped at all altitudes. The damping was also consistently observed in the vertical (Z) BPF peak illustrated in the spectra. These findings had a noteworthy effect on both the comfort reaction (Figure A-10, less uncomfortable) as well as the daily expected duration thresholds for potential health risk (Figure A-14, greater than four hours).

As mentioned in the 2007 study (Smith, et al. 2008), as well as the field studies conducted on other rotary wing platforms, the ISO 2631-1 Comfort Reactions are based on likely reactions of occupants during public transportation. These reactions are considered independent of exposure time. It is expected that military aircrew, who are continuously performing critical tasks, are

typically exposed on a daily basis to more substantial vibration for longer periods of time that may contribute to fatigue and even pain, with symptom onset being time-dependent.

Figure 8 compares the seat pan $a_{v,daily}$ from several rotary-wing/tilt-rotor aircraft that have been assessed for health risk in accordance with ISO 2631-1. For the CV-22, the assessments for both cruise in APLN mode and cruise in CONV mode are included. For the remaining aircraft, the data are associated with cruise during level flight. Each aircraft and/or flight mode shown in Figure 8 is annotated with the same-colored symbol. All aircraft and most of the stations have shown the potential for health risk in less than 8 hours of daily occupational exposures. The relatively low exposure duration thresholds for potential health risk are particularly noteworthy for the H-60 and Chinook platforms.

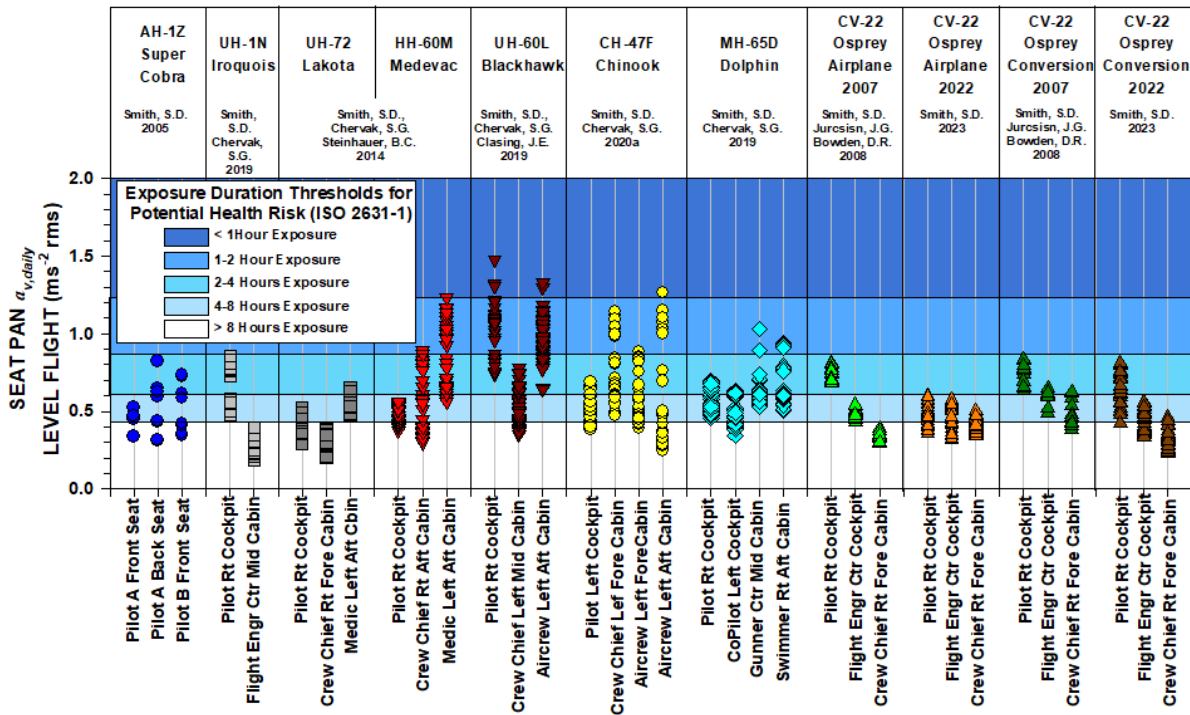


Figure 8. Comparison of the Seat Pan $a_{v,daily}$ Among Rotary-Wing/Tilt-Rotor Aircraft

In summary, the results of the assessments on the CV-22 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, 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, that could lead to the improvement of exposure guidelines directed towards military aircrew, as well as the development of more robust discomfort and pain mitigation strategies.

6.0 REFERENCES

- American Conference of Governmental Industrial Hygienist (ACGIH®), Threshold Limit Values (TLVs®) and Biological Exposure Indices (BEIs®), Signature Publications, 2023.
- Couvreur, C., *FILTBANK - One-Third-Octave Band Frequency Analyzer* [computer program, MATLAB®], Faculte Polytechnique de Mons, Belgium, 1997.
- Department of Defense, *Department of Defense Design Criteria Standard, Human Engineering*, MIL-STD-1472H, Sep, 2020.
- Hamon, K., Healing, R., Contarino, R., Ellenbecker, D. *Business Case Analysis: Improve Combat Readiness and Mission Effectiveness by Eliminating Avoidable Helicopter Seating Related Injuries*, R Cubed Consulting, Final Report, OUSD (AT&L), DUSD (I&E), 2012.
- International Organization for Standardization, *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements*, ISO 2631-1: 1997. Geneva, Switzerland.
- International Organization for Standardization, *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements-Amendment 1*, ISO 2631-1/Amd1:2010. Geneva, Switzerland.
- Smith, S. D., *Super Cobra (AH-1Z) Human Vibration Evaluation*, AFRL-HE-WP-TR-2005-0114, Air Force Research Laboratory, Wright-Patterson AFB OH, August, 2005.
- Smith S.D., Jurcsisn, J.G., Bowden, D. R., *CV-22 Human Vibration Evaluation*, AFRL-RH-WP-TR-2008-0095, Air Force Research Laboratory, Human Effectiveness Directorate, Wright-Patterson AFB OH, 2008.
- Smith S.D. & Chervak, S.G., *Vibration Exposure Characterization and Health Risk Assessment of the MH-65D Dolphin*, AFRL-RH-WP-TR-2019-0103, Air Force Research Laboratory, Wright-Patterson AFB OH, 2019.
- Smith S.D. & Chervak, S.G., *Vibration Exposure Characterization and Health Risk Assessment of the CH-47F Chinook*, AFRL-RH-WP-TR-2020-0074, Air Force Research Laboratory, Wright-Patterson AFB OH, 2020a.
- Smith, S.D. & Chervak, S.G., *Vibration Exposure Characterization and Health Risk Assessment of the UH-1N Iroquois*, AFRL-RH-WP-TR-2020-0129, Wright-Patterson AFB OH, 2020b.
- Smith S.D., Chervak, S., Steinhauer, B., *Vibration Characterization and Health Risk Assessment of the Vermont Army National Guard UH-72 Lakota and HH-60M Medevac*, AFRL-RH-WP-TR-2014-0053, Air Force Research Laboratory, Wright-Patterson AFB OH, 2014.

Smith S.D., Chervak, S.G., Clasing, J.E., *Vibration Exposure Characterization and Health Risk Assessment of the UH-60L Blackhawk*, AFRL-RH-WP-TR-2019-0032, Air Force Research Laboratory, Wright-Patterson AFB OH, 2019.

Welch, P. D., "The Use of Fast Fourier Transform for the Estimation of Power spectra: A method Based on Time Averaging Over Short, Modified Periodograms," *IEEE Trans. Audio Electroacoust.*, AU-15, Jun 1967, pp. 70-73.

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711th Human Performance Wing
AC	Aircrew
ACGIH	American Conference of Governmental Industrial Hygienist
AGL	Above Ground Level
APLN	Airplane
APHC	Army Public Health Center
AFRL	Air Force Research Laboratory
AFSOC	Air Force Special Operations Command
AVSS	Active Vibration Suppression System
BCA	Business Case Analysis
BPF	Blade Passage Frequency
CBDN	Collaborative Biomechanics Data Network
CONV	Conversion
DAU	Data Acquisition Units
DHP	Defense Health Program
DUSD I&E	Deputy Under Secretary of Defense Installations and Environment
FE	Flight Engineer
FLTS	Flight Test Squadron
HGCZ	Health Guidance Caution Zone
Hz	Hertz (cycles per second)
IGE	In Ground Effect
IRB	Institutional Review Board
ISO	International Organization for Standardization
K	One Thousand (1000)
MIL-STD	Military Standard
MSL	Mean Sea Level
NDCEE	National Defense Center for Energy and Environment
NHSR	Not Human Subject Research
OGE	Out of Ground Effect
OUSD ATL	Office of the Under Secretary of Defense for Acquisition, Technology and Logistics
PI	Pilot
PRF	Propeller Rotation Frequency
RDT&E	Research, Development, Test and Evaluation
REVER	Remote Vibration Environment Recorder
RH	Human Effectiveness Directorate
SOS	Special Operations Squadron
RPM	Revolutions per Minute
SOW	Special Operations Wing
TLV	Threshold Limit Value
VT ARNG	Vermont Army National Guard
ft	feet
rms	root-mean-square

%	percent
a_{rms}	root-mean-square (rms) acceleration
a_l	Overall unweighted rms acceleration in direction l (X, Y, Z)
a_{li}	Overall unweighted rms acceleration associated with direction l for the i th one-third octave frequency component
$a_{v,daily}$	Vector sum of the daily overall weighted rms accelerations in directions X, Y, Z
a_{wl}	Overall weighted rms acceleration in direction l (X, Y, Z)
$a_{wl,daily}$	Daily overall weighted rms acceleration in direction l (X, Y, Z)
k_l	Multiplying Factor for the l direction (ISO 2631-1)
$oVTV(s)$	Overall Vibration Total Value(s)
$pVTV(s)$	Point Vibration Total Value(s)
W_{li}	Frequency Weighting associated with direction l for the specific measurement site (seat pan or seat back) for the i th one-third octave center frequency component
X	Fore-and-Aft Axis or Direction
Y	Lateral Axis or Direction
Z	Vertical Axis or Direction

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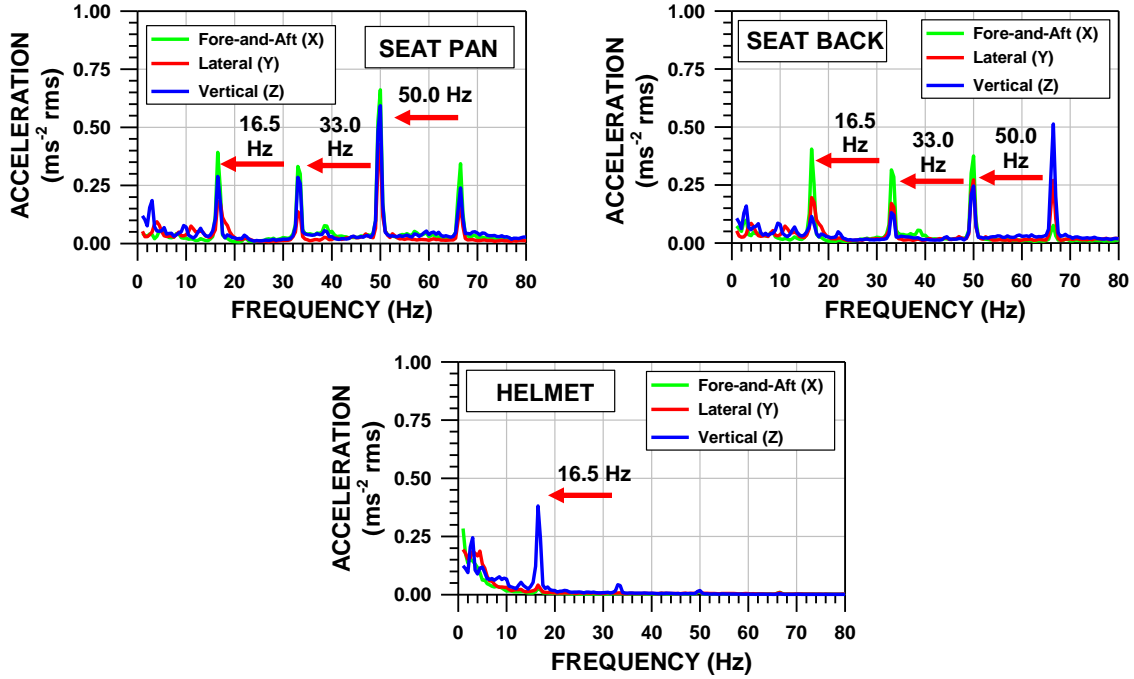
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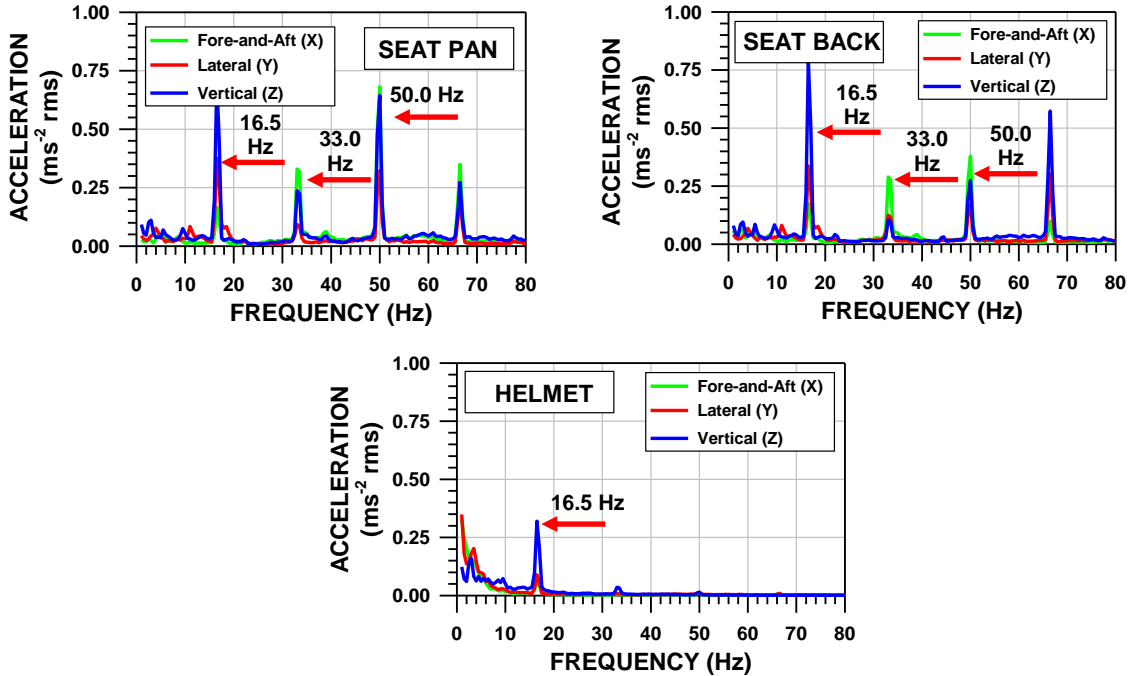
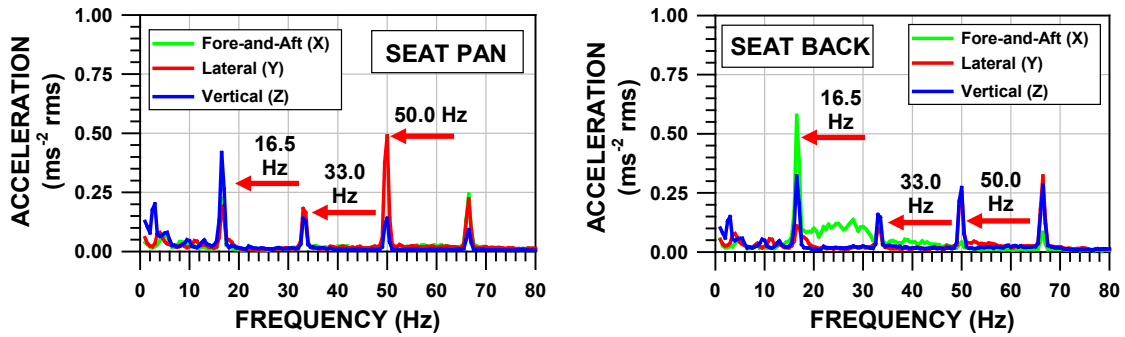


Figure A-1. Example of the CV-22 Unweighted Multi-Axis Acceleration Spectra During Cruise Flight in APLN Mode (10K ft MSL) at the Pilot Cockpit Station

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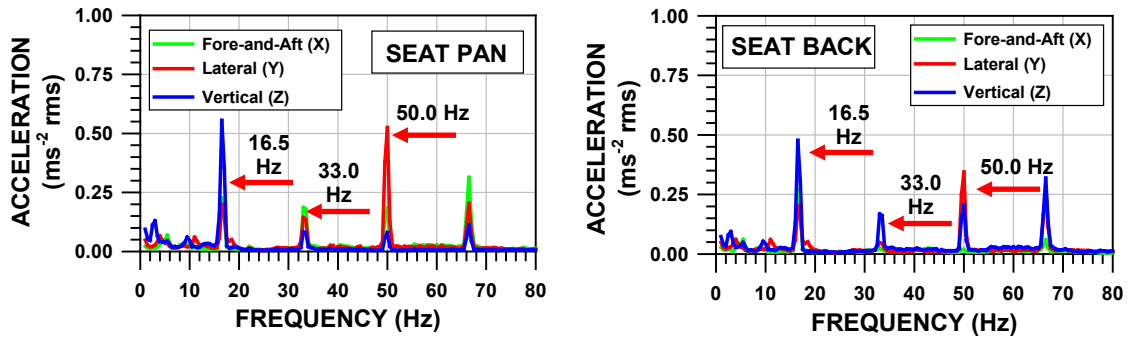
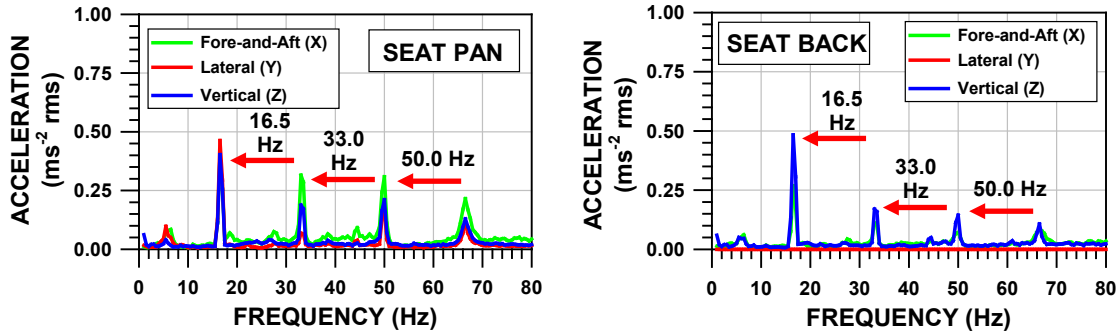


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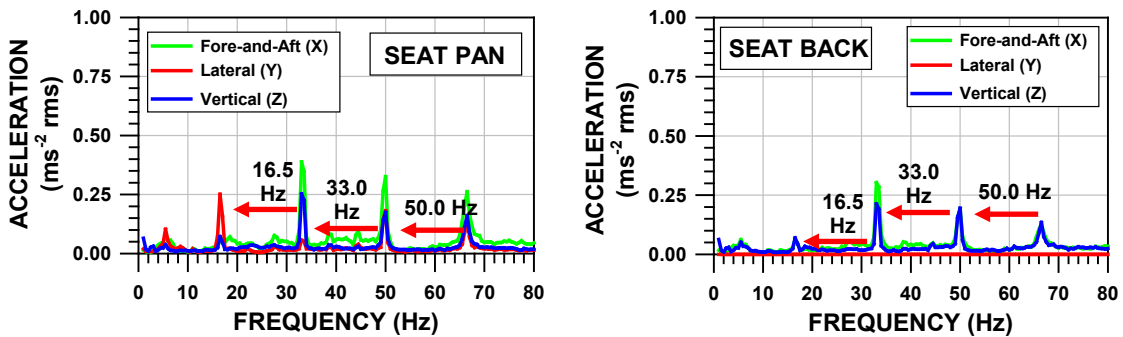
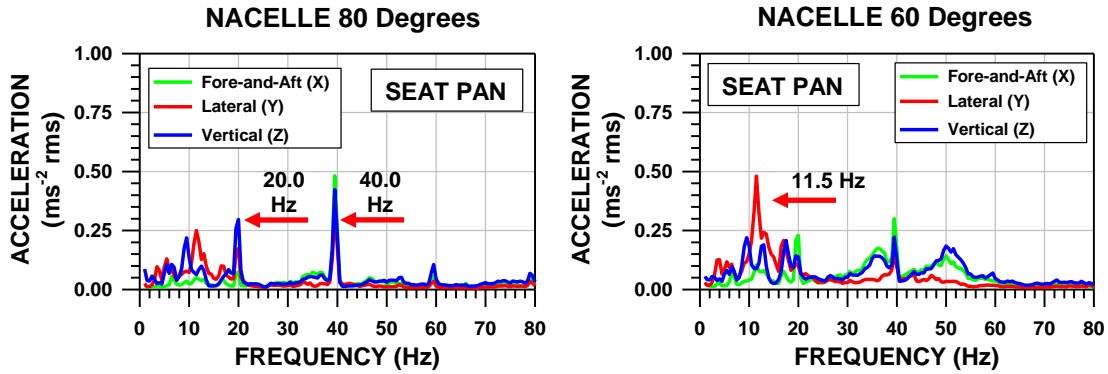


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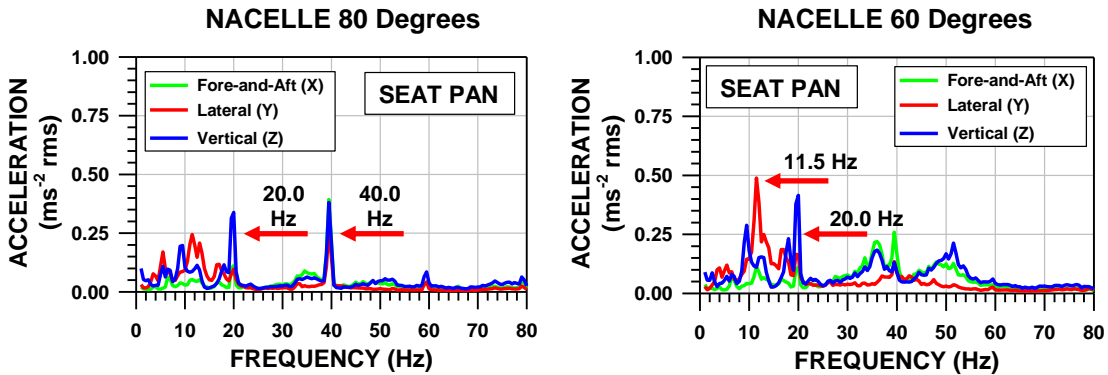
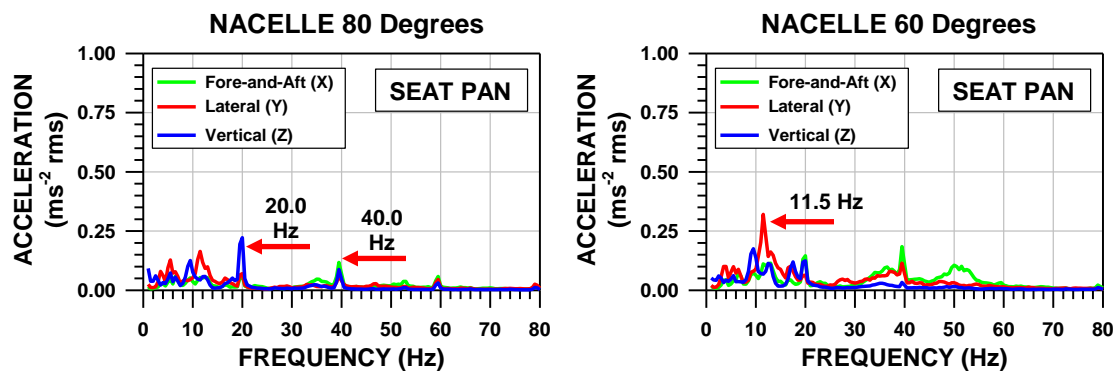


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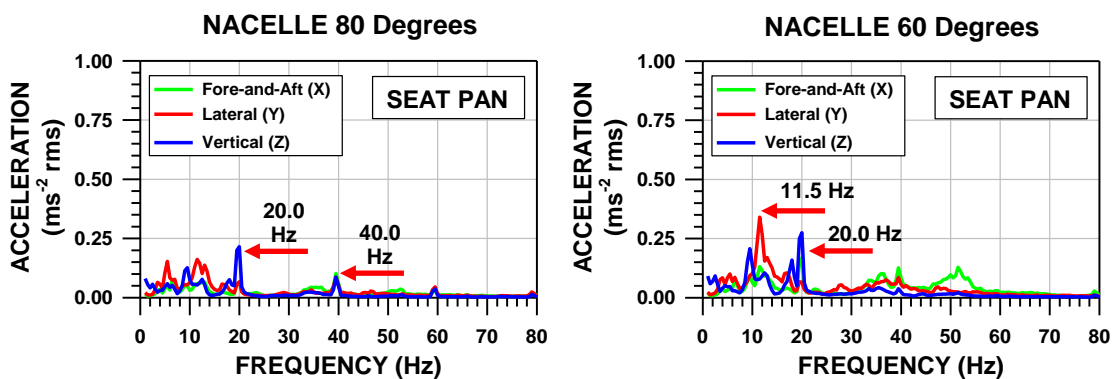
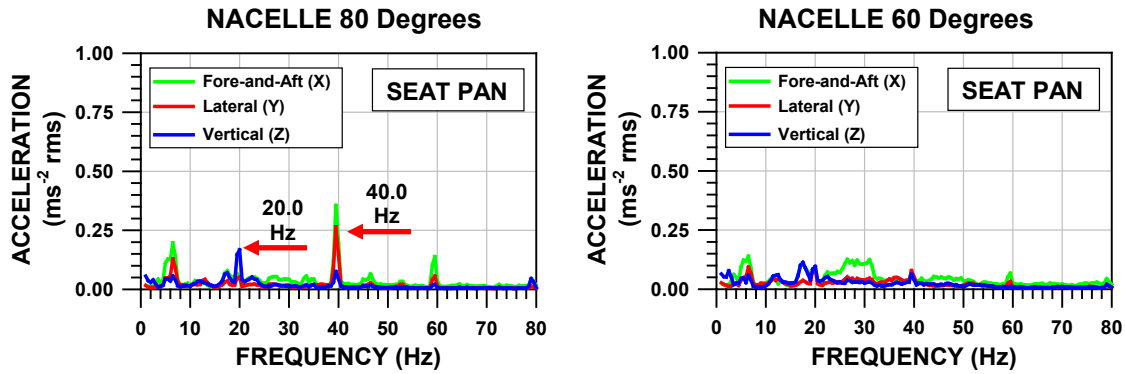


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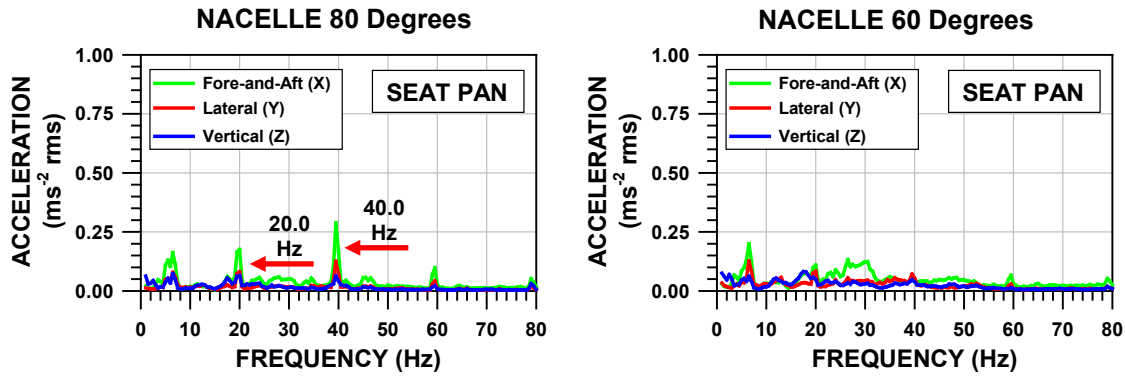


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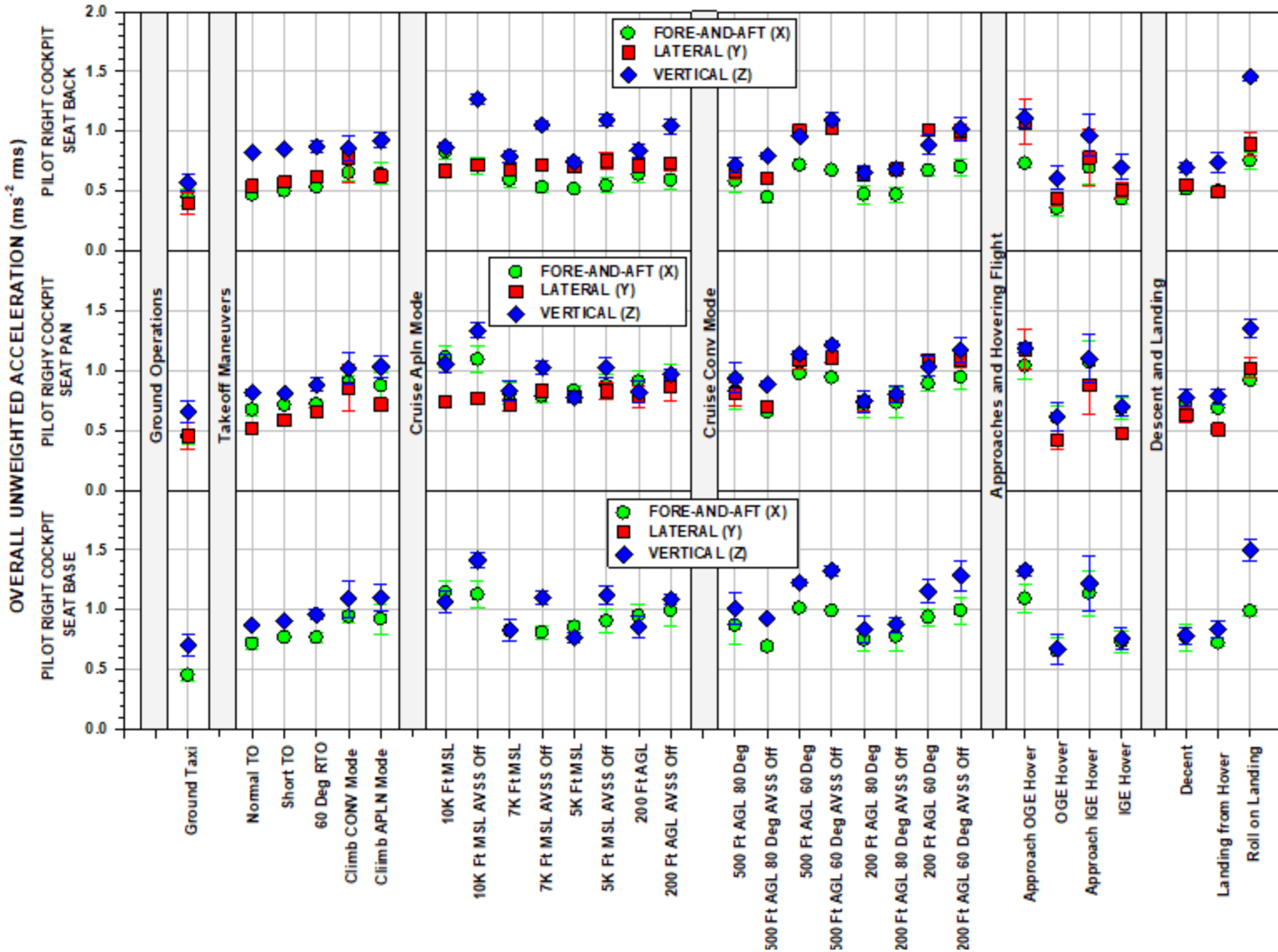


Figure A- 7. Mean Overall Unweighted Accelerations ± One Standard Deviation at the CV-22 Pilot Cockpit Station

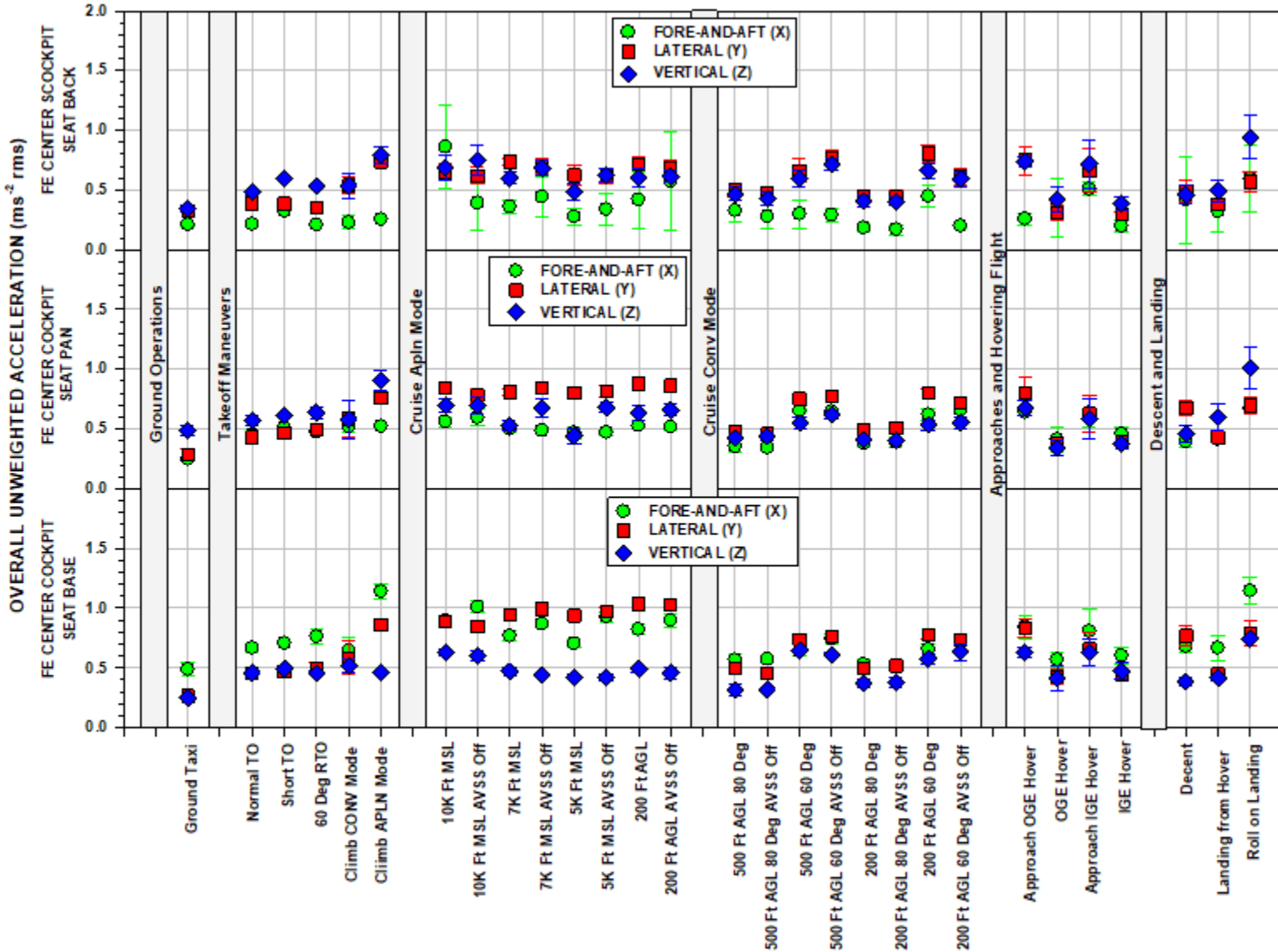


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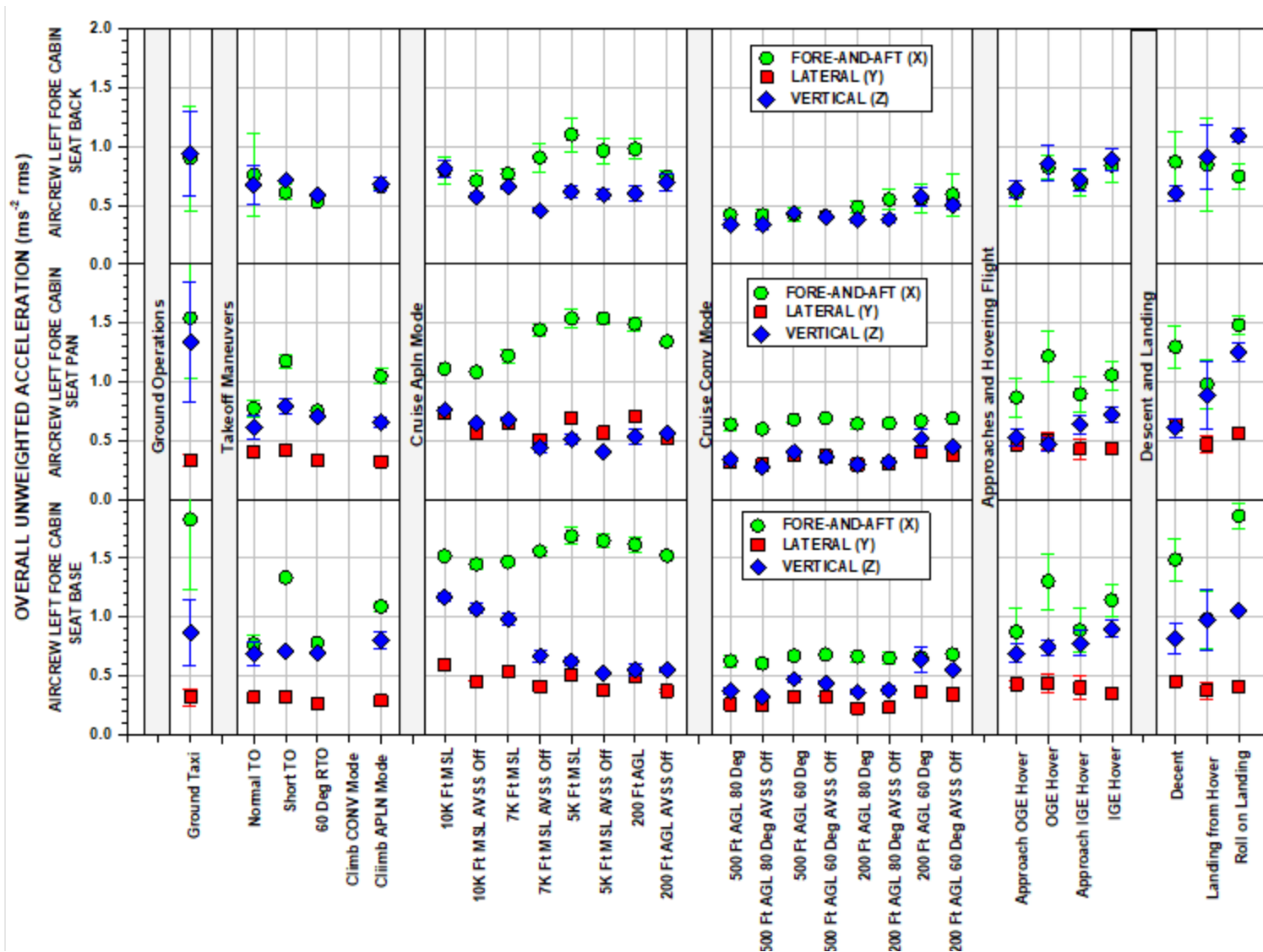


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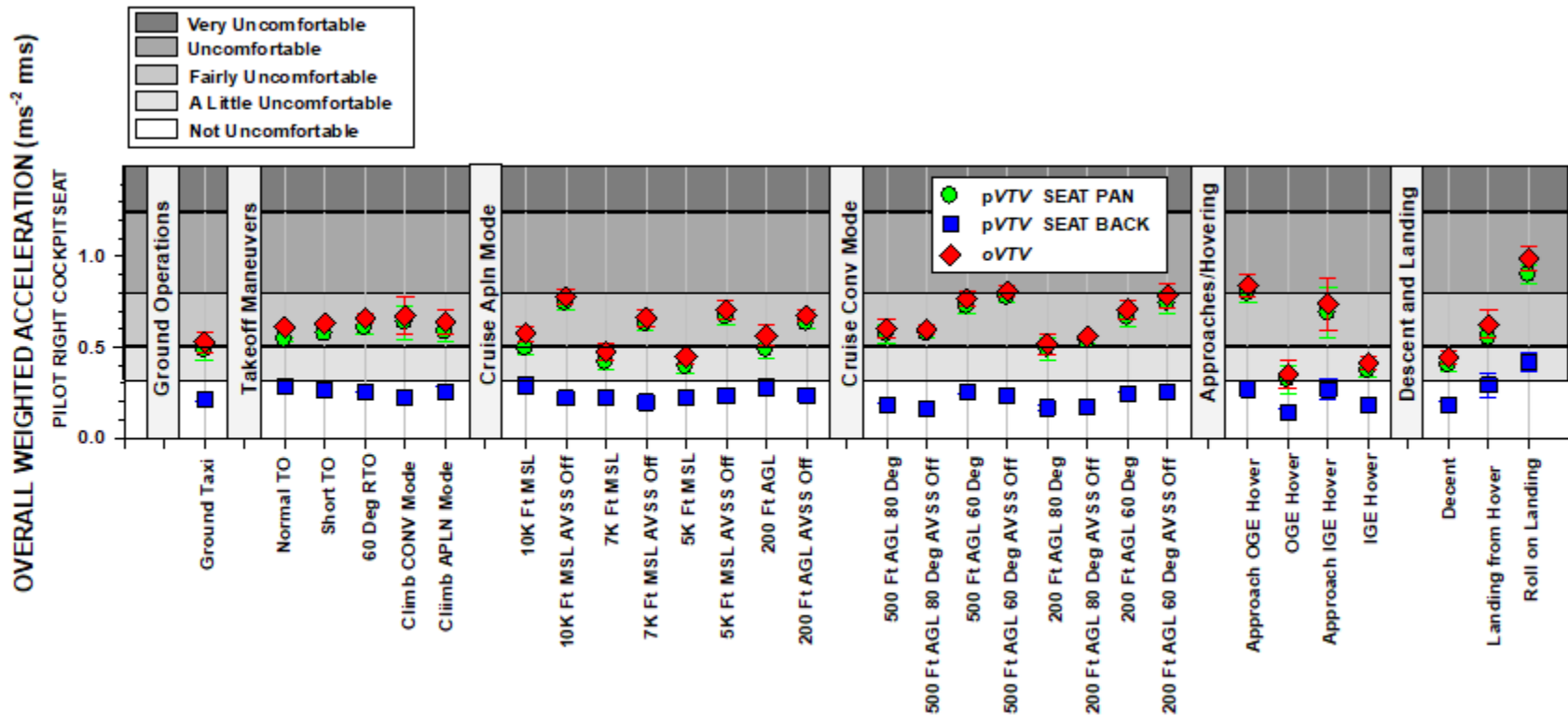


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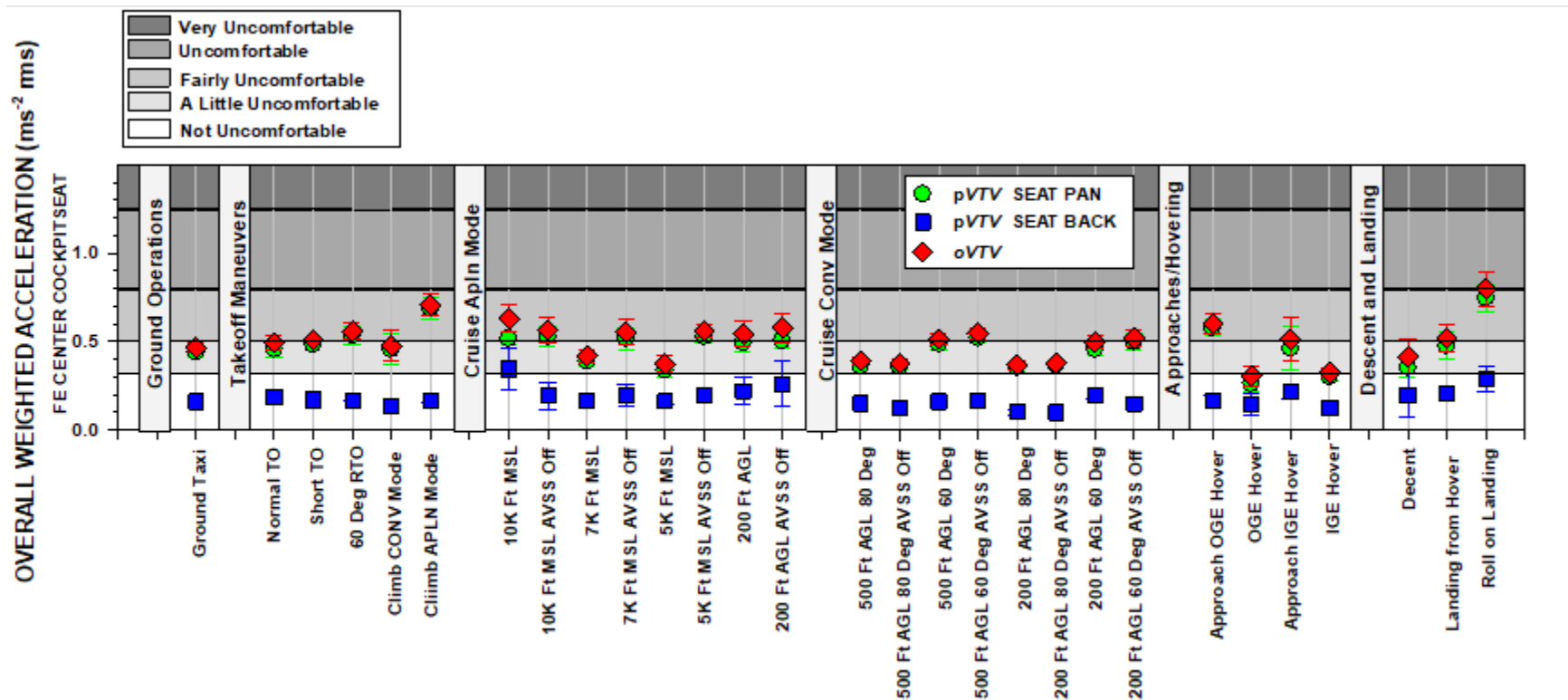


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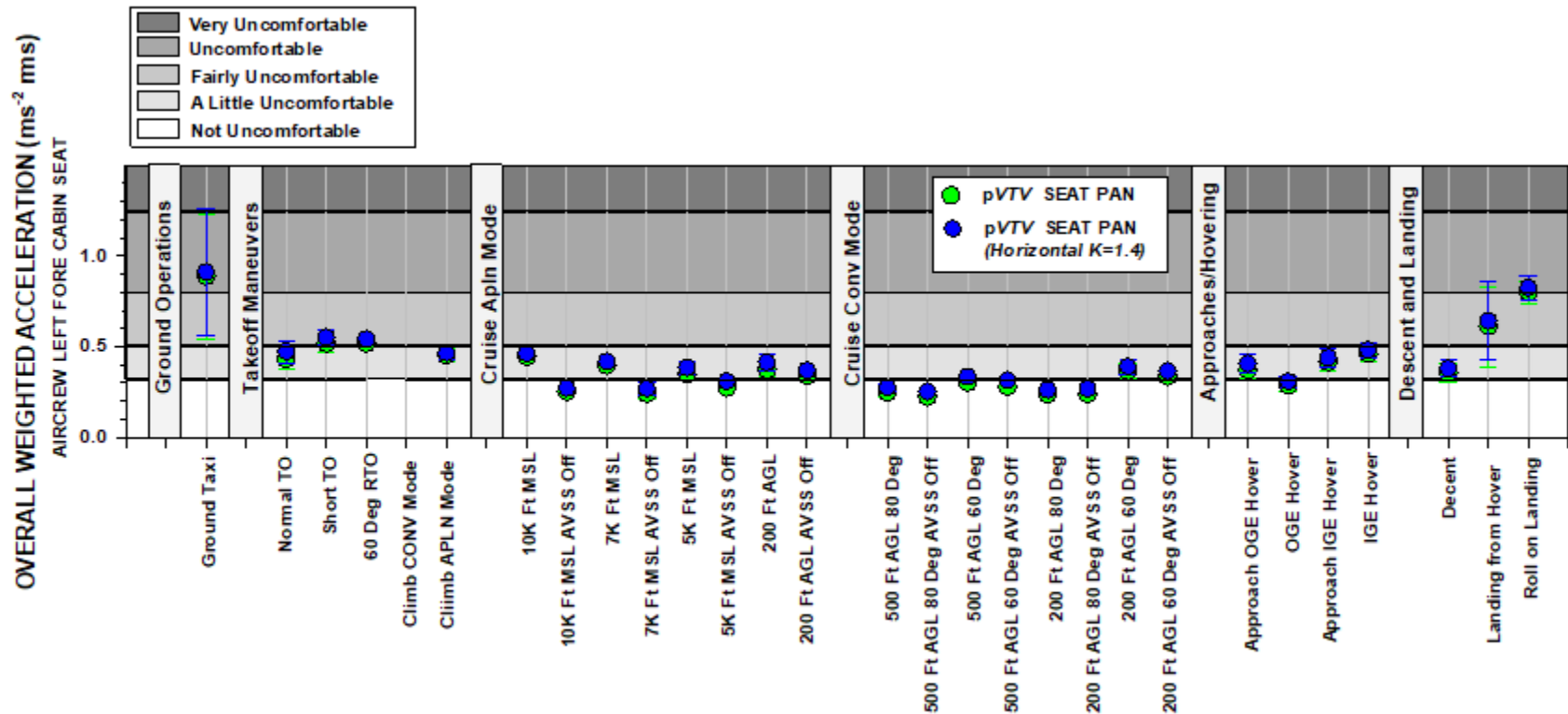


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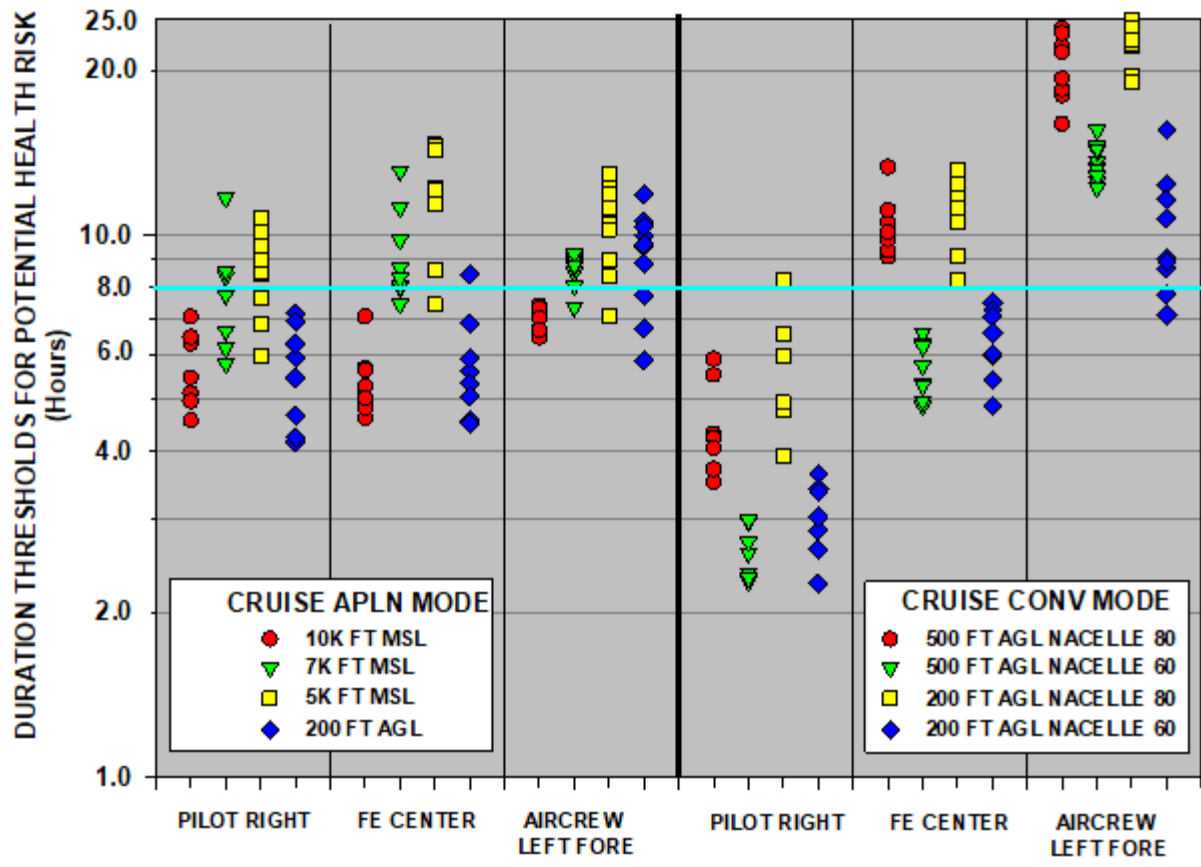


Figure A- 13. CV-22 Cruise Flight Exposure Duration Thresholds for “Potential Health Risk” in a 24-Hour Period (ISO 2631-1)

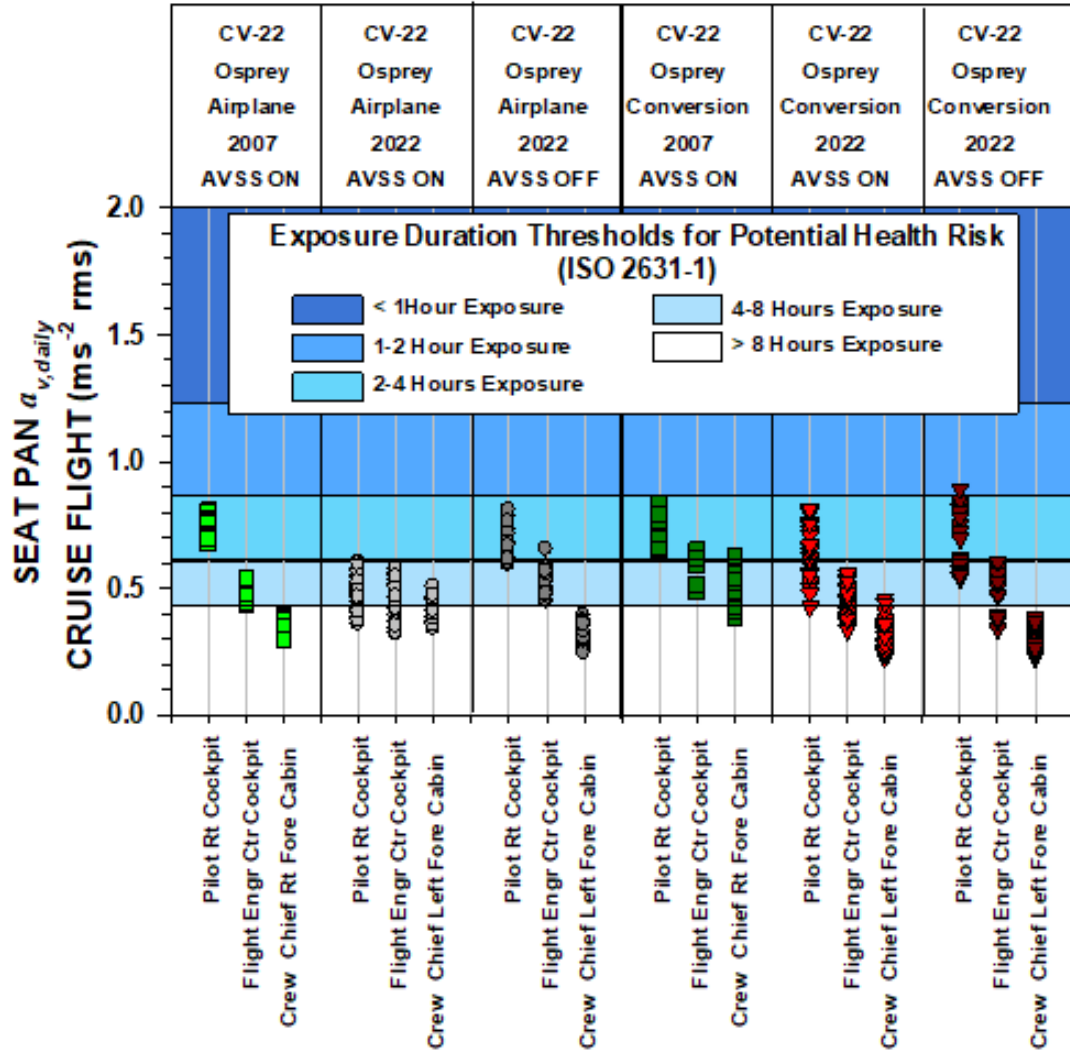


Figure A- 14. CV-22 Aircrew Seat Pan $a_{v,daily}$

Table A- 1. REVER Component Details

Component	Dimensions (L/W/H cm)	Weight (Kg)
Small DAUs	9.5/7.0/2.8	0.370 w/cables
Large Batteries	10.0/7.0/3.5	0.645
Small Batteries	9.0/5.0/3.5	0.395
Accelerometer Packs (Entran EGAX-25; TE Connectivity/Masurement Specialties EGAXT-25)	1.9 (diameter) 0.86 (thickness)	0.005 (0.060 w/ cable)
Accelerometer Pad (Entran EGAX-25; TE Connectivity/Masurement Specialties EGAXT-25)	(Ride Quality Meter, RQM) 20.0 (diameter)	0.340 w/ cables
Triggers	7.6 (length) 2.2 (diameter)	0.030 w/cable

Table A- 2. CV-22 Pilot Cockpit Station Overall Unweighted and Weighted Seat Pan Accelerations (a_l , $a_{wl,daily}$), $a_{v,daily}$, and Exposure Duration Thresholds for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

ALTITUDE ft	RECORD #	a_x	a_y	a_z	$a_{wx,daily}$	$a_{wy,daily}$	$a_{wz,daily}$	$a_{v,daily}$	DURATION THRESHOLDS POTENTIAL HLTH RISKS	DURATION THRESHOLDS HLTH RISKS LIKELY	DURATION THRESHOLDS POTENTIAL HLTH RISKS	DURATION THRESHOLDS HLTH RISKS LIKELY
									$a_{wz,daily}$	$a_{wz,daily}$	$a_{v,daily}$	$a_{v,daily}$
ACCELERATION (ms ⁻² rms)									EXPOSURE DURATION (Hours)			
10K MSL	13	1.163	0.770	1.116	0.151	0.168	0.493	0.542	6.174	24.696	5.104	20.417
10K MSL	14	1.170	0.797	1.116	0.173	0.186	0.515	0.575	5.651	22.605	4.545	18.179
10K MSL	15	1.255	0.804	1.163	0.160	0.165	0.492	0.543	6.207	24.827	5.095	20.381
10K MSL	16	1.161	0.736	1.094	0.158	0.167	0.472	0.525	6.736	26.943	5.446	21.783
10K MSL	17	1.041	0.684	1.020	0.131	0.130	0.452	0.488	7.349	29.394	6.298	25.191
10K MSL	18	0.969	0.687	0.934	0.132	0.149	0.438	0.481	7.812	31.247	6.471	25.885
10K MSL	19	1.007	0.653	0.940	0.137	0.150	0.414	0.461	8.769	35.074	7.064	28.256
10K MSL	20	1.110	0.758	1.066	0.184	0.222	0.470	0.552	6.785	27.139	4.931	19.723
MEAN		1.109	0.736	1.056	0.153	0.167	0.468	0.521	6.935	27.741	5.619	22.477
STDEV		0.097	0.056	0.084	0.019	0.028	0.033	0.040	1.009	4.035	0.884	3.537
7K MSL	32	0.802	0.728	0.887	0.145	0.188	0.432	0.493	8.034	32.135	6.179	24.717
7K MSL	33	0.790	0.732	0.832	0.113	0.176	0.387	0.440	10.005	40.020	7.742	30.967
7K MSL	34	0.901	0.748	0.885	0.125	0.175	0.424	0.475	8.344	33.375	6.642	26.569
7K MSL	35	0.785	0.714	0.792	0.107	0.132	0.383	0.419	10.220	40.882	8.544	34.176
7K MSL	36	0.870	0.796	0.821	0.121	0.144	0.379	0.423	10.448	41.793	8.379	33.515
7K MSL	37	0.930	0.690	0.975	0.153	0.211	0.438	0.509	7.826	31.304	5.782	23.130
7K MSL	38	0.677	0.630	0.722	0.093	0.123	0.324	0.358	14.324	57.297	11.675	46.699
7K MSL	39	0.675	0.663	0.713	0.117	0.175	0.362	0.418	11.478	45.913	8.569	34.275
MEAN		0.804	0.713	0.828	0.122	0.165	0.391	0.442	10.085	40.340	7.939	31.756
STDEV		0.095	0.052	0.088	0.019	0.030	0.039	0.049	2.152	8.607	1.866	7.465
5K MSL	51	0.870	0.864	0.841	0.143	0.192	0.373	0.443	10.799	43.195	7.645	30.578
5K MSL	52	0.806	0.796	0.747	0.112	0.181	0.320	0.384	14.648	58.594	10.159	40.635
5K MSL	53	0.932	0.830	0.819	0.128	0.158	0.341	0.396	12.930	51.720	9.544	38.174
5K MSL	54	0.840	0.779	0.703	0.124	0.149	0.319	0.374	14.722	58.888	10.748	42.991
5K MSL	55	0.784	0.753	0.743	0.123	0.207	0.345	0.420	12.632	50.527	8.487	33.949
5K MSL	56	0.819	0.740	0.773	0.138	0.183	0.351	0.419	12.182	48.729	8.534	34.135
5K MSL	57	0.811	0.722	0.823	0.156	0.195	0.435	0.501	7.938	31.752	5.970	23.880
5K MSL	58	0.834	0.791	0.780	0.156	0.205	0.391	0.468	9.827	39.307	6.856	27.422
5K MSL	50	0.745	0.750	0.724	0.124	0.178	0.346	0.408	12.530	50.119	9.003	36.011
MEAN		0.827	0.780	0.772	0.134	0.183	0.358	0.424	12.023	48.092	8.549	34.197
STDEV		0.053	0.045	0.047	0.015	0.020	0.037	0.041	2.198	8.793	1.540	6.158
200 AGL	68	1.033	0.952	0.803	0.155	0.182	0.390	0.457	9.867	39.468	7.169	28.676
200 AGL	69	1.042	0.738	1.007	0.172	0.242	0.523	0.601	5.488	21.952	4.151	16.605
200 AGL	70	0.827	0.736	0.818	0.167	0.230	0.492	0.568	6.197	24.787	4.648	18.593
200 AGL	71	0.810	0.741	0.748	0.161	0.200	0.432	0.502	8.045	32.180	5.949	23.796
200 AGL	72	0.882	0.684	0.845	0.151	0.195	0.464	0.525	6.970	27.881	5.440	21.761
200 AGL	73	0.811	0.694	0.728	0.149	0.191	0.424	0.488	8.340	33.359	6.288	25.151
200 AGL	74	0.827	0.811	0.710	0.151	0.209	0.388	0.466	9.984	39.938	6.921	27.683
200 AGL	75	1.008	0.908	0.875	0.219	0.295	0.469	0.596	6.811	27.243	4.228	16.911
MEAN		0.810	0.701	0.731	0.149	0.196	0.402	0.472	7.100	28.400	5.148	20.593
STDEV		0.300	0.263	0.272	0.054	0.075	0.144	0.170	2.397	9.586	1.745	6.981

Table A- 3. CV-22 Flight Engineer (FE) Cockpit Station Overall Unweighted and Weighted Seat Pan Accelerations (a_x , a_y , a_z , $a_{wx,daily}$, $a_{wy,daily}$, $a_{wz,daily}$, $a_{v,daily}$), and Exposure Duration Thresholds for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

ALTITUDEft	RECORD #	a_x	a_y	a_z	$a_{wx,daily}$	$a_{wy,daily}$	$a_{wz,daily}$	$a_{v,daily}$	DURATION THRESHOLDS POTENTIAL HLTH RISKS	DURATION THRESHOLDS HLTH RISKS LIKELY	DURATION THRESHOLDS POTENTIAL HLTH RISKS	DURATION THRESHOLDS HLTH RISKS LIKELY
									$a_{wz,daily}$	$a_{wz,daily}$	$a_{v,daily}$	$a_{v,daily}$
ACCELERATION (ms ⁻² rms)									EXPOSURE DURATION (Hours)			
10K MSL	13	0.580	0.867	0.762	0.105	0.141	0.544	0.572	5.067	20.267	4.588	18.353
10K MSL	14	0.560	0.855	0.739	0.118	0.147	0.523	0.556	5.488	21.952	4.854	19.415
10K MSL	15	0.589	0.862	0.707	0.116	0.144	0.501	0.534	5.967	23.866	5.252	21.009
10K MSL	16	0.588	0.839	0.730	0.100	0.139	0.533	0.559	5.284	21.136	4.792	19.169
10K MSL	17	0.529	0.834	0.672	0.090	0.114	0.493	0.514	6.172	24.686	5.676	22.704
10K MSL	18	0.536	0.862	0.683	0.096	0.124	0.492	0.516	6.199	24.797	5.627	22.509
10K MSL	19	0.479	0.773	0.580	0.105	0.141	0.426	0.461	8.273	33.093	7.069	28.276
10K MSL	20	0.621	0.868	0.688	0.150	0.186	0.493	0.548	6.172	24.686	5.000	19.999
MEAN		0.560	0.845	0.695	0.110	0.142	0.501	0.533	6.078	24.311	5.357	21.429
STDEV		0.045	0.032	0.056	0.019	0.021	0.036	0.035	0.990	3.961	0.794	3.174
7K MSL	32	0.521	0.803	0.576	0.114	0.161	0.403	0.449	9.222	36.889	7.446	29.784
7K MSL	33	0.499	0.827	0.505	0.091	0.151	0.350	0.392	12.231	48.924	9.768	39.071
7K MSL	34	0.492	0.851	0.560	0.103	0.141	0.397	0.434	9.522	38.088	7.979	31.917
7K MSL	35	0.470	0.817	0.558	0.078	0.111	0.393	0.416	9.722	38.887	8.683	34.733
7K MSL	36	0.525	0.823	0.485	0.102	0.121	0.330	0.366	13.816	55.264	11.216	44.865
7K MSL	37	0.550	0.818	0.566	0.110	0.169	0.382	0.432	10.285	41.139	8.045	32.181
7K MSL	38	0.479	0.795	0.451	0.075	0.105	0.313	0.339	15.291	61.166	13.081	52.322
7K MSL	39	0.454	0.751	0.538	0.092	0.152	0.386	0.425	10.073	40.290	8.313	33.253
MEAN		0.499	0.811	0.530	0.096	0.139	0.369	0.406	11.270	45.081	9.316	37.266
STDEV		0.032	0.029	0.045	0.014	0.024	0.034	0.038	2.256	9.024	1.938	7.752
5K MSL	51	0.512	0.828	0.465	0.113	0.142	0.314	0.363	15.194	60.777	11.395	45.582
5K MSL	52	0.482	0.828	0.388	0.092	0.149	0.267	0.320	20.994	83.976	14.673	58.692
5K MSL	53	0.465	0.794	0.386	0.115	0.130	0.270	0.321	20.576	82.305	14.557	58.229
5K MSL	54	0.380	0.725	0.391	0.101	0.123	0.281	0.323	18.956	75.825	14.358	57.432
5K MSL	55	0.450	0.748	0.416	0.117	0.178	0.294	0.363	17.389	69.557	11.387	45.549
5K MSL	56	0.522	0.871	0.424	0.122	0.152	0.292	0.351	17.617	70.466	12.191	48.763
5K MSL	57	0.493	0.820	0.568	0.122	0.148	0.407	0.449	9.078	36.310	7.430	29.719
5K MSL	58	0.510	0.854	0.508	0.127	0.174	0.358	0.417	11.737	46.946	8.607	34.428
5K MSL	50	0.410	0.739	0.418	0.105	0.151	0.301	0.352	16.578	66.313	12.077	48.310
MEAN		0.469	0.801	0.440	0.113	0.150	0.309	0.362	16.458	65.830	11.853	47.411
STDEV		0.048	0.052	0.062	0.011	0.018	0.045	0.045	3.943	15.771	2.555	10.221
200 AGL	68	0.550	0.976	0.528	0.117	0.152	0.375	0.4214	10.650	42.598	8.447	33.786
200 AGL	69	0.549	0.879	0.707	0.149	0.204	0.516	0.5742	5.636	22.543	4.549	18.197
200 AGL	70	0.536	0.834	0.715	0.138	0.188	0.528	0.5774	5.381	21.522	4.500	17.998
200 AGL	71	0.543	0.837	0.627	0.137	0.176	0.468	0.5179	6.854	27.418	5.591	22.366
200 AGL	72	0.525	0.885	0.667	0.121	0.161	0.491	0.5309	6.217	24.868	5.322	21.289
200 AGL	73	0.526	0.837	0.607	0.132	0.159	0.459	0.5034	7.123	28.491	5.919	23.674
200 AGL	74	0.485	0.883	0.553	0.137	0.170	0.413	0.4671	8.781	35.125	6.874	27.496
200 AGL	75	0.522	0.913	0.649	0.166	0.231	0.466	0.5457	6.913	27.654	5.038	20.151
MEAN		0.529	0.880	0.632	0.137	0.180	0.465	0.517	7.194	28.777	5.780	23.120
STDEV		0.021	0.048	0.067	0.015	0.026	0.051	0.053	1.746	6.983	1.324	5.297

Table A- 4. CV-22 Aircrew Cabin Station Overall Unweighted and Weighted Seat Pan Accelerations(a_x , $a_{wl,daily}$), $a_{v,daily}$, and Exposure Duration Thresholds for Potential Health Risk (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

ALTITUDE ft	RECORD #	a_x	a_y	a_z	$a_{wx,daily}$	$a_{wy,daily}$	$a_{wz,daily}$	$a_{v,daily}$	DURATION THRESHOLDS POTENTIAL HLTH RISKS	DURATION THRESHOLDS POTENTIAL HLTH RISKS LIKELY	DURATION THRESHOLDS POTENTIAL HLTH RISKS	DURATION THRESHOLDS POTENTIAL HLTH RISKS LIKELY
									$a_{wz,daily}$	$a_{wz,daily}$	$a_{v,daily}$	$a_{v,daily}$
ACCELERATION (ms ⁻² rms)									EXPOSURE DURATION (Hours)			
10K MSL	22	1.120	0.744	0.748	0.132	0.127	0.446	0.482	7.554	30.217	6.464	25.855
10K MSL	23	1.102	0.716	0.757	0.126	0.125	0.439	0.474	7.770	31.081	6.681	26.723
10K MSL	24	1.085	0.720	0.758	0.130	0.125	0.419	0.456	8.542	34.167	7.205	28.819
10K MSL	25	1.098	0.748	0.770	0.125	0.126	0.417	0.453	8.614	34.456	7.301	29.202
10K MSL	26	1.105	0.743	0.754	0.123	0.123	0.415	0.450	8.696	34.782	7.398	29.592
10K MSL	27	1.119	0.726	0.754	0.125	0.123	0.421	0.456	8.466	33.865	7.219	28.876
10K MSL	28	1.112	0.727	0.731	0.128	0.123	0.420	0.456	8.494	33.978	7.205	28.819
10K MSL	29	1.119	0.745	0.756	0.128	0.124	0.416	0.453	8.664	34.656	7.319	29.275
10K MSL	30	1.115	0.755	0.775	0.135	0.127	0.424	0.462	8.363	33.452	7.017	28.068
10K MSL	31	1.105	0.733	0.786	0.134	0.125	0.438	0.474	7.835	31.341	6.667	26.667
MEAN		1.108	0.736	0.759	0.129	0.125	0.425	0.462	8.300	33.200	7.047	28.190
STDEV		0.011	0.013	0.015	0.004	0.002	0.011	0.011	0.417	1.670	0.327	1.307
7K MSL	45	1.149	0.654	0.701	0.127	0.113	0.369	0.406	11.016	44.065	9.085	36.339
7K MSL	46	1.170	0.666	0.699	0.131	0.114	0.371	0.409	10.913	43.652	8.948	35.791
7K MSL	47	1.167	0.641	0.694	0.130	0.111	0.375	0.412	10.674	42.695	8.842	35.369
7K MSL	48	1.188	0.644	0.672	0.131	0.114	0.369	0.408	10.996	43.986	9.006	36.024
7K MSL	49	1.197	0.649	0.684	0.139	0.118	0.378	0.420	10.506	42.023	8.521	34.086
7K MSL	50	1.193	0.629	0.682	0.138	0.117	0.392	0.432	9.744	38.976	8.034	32.137
7K MSL	51	1.257	0.664	0.708	0.163	0.129	0.401	0.452	9.319	37.275	7.355	29.421
7K MSL	52	1.270	0.669	0.648	0.141	0.116	0.360	0.403	11.599	46.396	9.216	36.863
7K MSL	53	1.294	0.633	0.647	0.144	0.116	0.371	0.415	10.882	43.527	8.717	34.868
7K MSL	54	1.301	0.641	0.638	0.139	0.118	0.371	0.413	10.910	43.640	8.786	35.143
MEAN		1.219	0.649	0.677	0.138	0.117	0.376	0.417	10.656	42.623	8.651	34.604
STDEV		0.056	0.014	0.025	0.010	0.005	0.012	0.015	0.663	2.653	0.563	2.253
5K MSL	68	1.488	0.647	0.542	0.157	0.122	0.301	0.361	16.580	66.319	11.541	46.163
5K MSL	69	1.484	0.664	0.546	0.159	0.125	0.320	0.378	14.655	58.620	10.473	41.893
5K MSL	70	1.488	0.690	0.527	0.184	0.154	0.331	0.409	13.652	54.609	8.971	35.883
5K MSL	71	1.521	0.700	0.576	0.210	0.193	0.361	0.460	11.530	46.118	7.095	28.380
5K MSL	72	1.518	0.715	0.567	0.189	0.152	0.347	0.424	12.438	49.753	8.363	33.453
5K MSL	73	1.503	0.677	0.452	0.172	0.134	0.274	0.350	19.939	79.757	12.212	48.849
5K MSL	74	1.491	0.709	0.478	0.185	0.150	0.300	0.383	16.713	66.853	10.242	40.968
5K MSL	75	1.506	0.695	0.466	0.162	0.133	0.268	0.340	20.867	83.469	12.961	51.845
5K MSL	76	1.643	0.701	0.452	0.177	0.136	0.275	0.354	19.788	79.154	11.942	47.767
5K MSL	77	1.739	0.700	0.482	0.184	0.131	0.288	0.366	18.127	72.510	11.213	44.851
MEAN		1.538	0.690	0.509	0.178	0.143	0.307	0.382	16.429	65.716	10.501	42.005
STDEV		0.085	0.021	0.048	0.016	0.021	0.032	0.038	3.284	13.137	1.863	7.451
200 AGL	88	1.621	0.716	0.487	0.192	0.145	0.290	0.377	17.861	71.442	10.572	42.286
200 AGL	89	1.487	0.691	0.515	0.186	0.149	0.318	0.397	14.865	59.460	9.501	38.005
200 AGL	90	1.576	0.730	0.548	0.205	0.170	0.351	0.440	12.208	48.833	7.740	30.961
200 AGL	91	1.483	0.653	0.476	0.207	0.149	0.292	0.388	17.538	70.151	9.956	39.825
200 AGL	92	1.507	0.694	0.473	0.181	0.139	0.273	0.356	20.193	80.772	11.859	47.437
200 AGL	93	1.492	0.720	0.514	0.184	0.151	0.297	0.381	17.026	68.106	10.359	41.437
200 AGL	94	1.469	0.690	0.515	0.196	0.153	0.307	0.396	15.890	63.559	9.583	38.332
200 AGL	95	1.434	0.676	0.543	0.200	0.165	0.319	0.411	14.701	58.803	8.873	35.492
200 AGL	96	1.423	0.727	0.676	0.226	0.202	0.404	0.505	9.180	36.720	5.878	23.510
200 AGL	97	1.429	0.746	0.631	0.198	0.191	0.385	0.473	10.123	40.493	6.710	26.841
MEAN		1.492	0.704	0.538	0.198	0.161	0.324	0.412	14.958	59.834	9.103	36.413
STDEV		0.064	0.028	0.067	0.013	0.021	0.043	0.047	3.528	14.112	1.841	7.362