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VIBRATION EXPOSURE CHARACTERIZATION AND HEALTH RISK ASSESSMENT OF THE UH-1N IROQUOIS

Suzanne D. Smith, PhD
Consultant, Infoscitex
Air Force Research Laboratory

Mr. Steven G. Chervak
Army Public Health Center

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711TH HUMAN PERFORMANCE WING
AIRMAN SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
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DAVID BURCH, PhD
Core Research Area Lead
Biomedical Impact of Flight Branch
Airman Biosciences Division

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Suzanne D. Smith*
Steven G. Chervak**
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Wright-Patterson AFB OH 45433

**Army Public Health Center (APHC)
8252 Blackhawk Rd.
Aberdeen Proving Ground MD 21010

*Consultant, Infoscitex

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14. ABSTRACT This study characterized and assessed aircrew vibration during operation of the UH-1N Iroquois helicopter owned and operated by the 413th Flight Test Squadron, Duke Field, Eglin AFB 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 Defense 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 at the pilot station and flight engineer station, and on the pilot helmet. Data records were collected by aircraft task and the associated flight test conditions. Constant and proportional frequency bandwidth acceleration spectra were generated for each record, as were the unweighted and weighted overall accelerations (1-80 Hz). Most data showed a small spectral peak between 5 and 6 Hz associated with the propeller rotation frequency (PRF) of the two-bladed UH-1N. The next higher peak occurred between 10.5 and 11 Hz and was associated with the blade passage frequency (BPF). Additional notable peaks were also observed at multiples of the BPF. Based on the overall vibration total values at each station, comfort reactions (ISO 631-1) ranged from "a little uncomfortable" to "uncomfortable" at the pilot station, and ranged from "a little uncomfortable" to "fairly uncomfortable" at the flight engineer station. Based on the seat pan point vibration total value for health, the comfort reactions ranged from "not uncomfortable" to "fairly uncomfortable" at the flight engineer station. Based on the seat pan point vibration total value for level flight, the pilot station showed the potential for health risk in less than 8 hours and in as little as 2 to 3 hours. Likely health risks at the pilot station were associated with daily flights lasting over 8 hours. The flight engineer station showed the potential for health risk for daily exposures lasting greater than 8 hours and no likely health risk within a 24-hour period. In summary, these results, particularly at the pilot station, 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 a potential health risk according to the standards and guidelines.

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PREFACE

This report summarizes the vibration exposure assessment conducted on the UH-1N Iroquois helicopter owned and operated by the 413 Flight Test Squadron (FLTS) at Duke Field, Eglin AFB, FL in accordance with the 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 (MIL)-Standard (STD)-1472G Department of Defense Design Criteria Standard, Human Engineering (2012). The study is the last for 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 MH-65D Dolphin 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 Human Performance Wing (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. The Air Force Research Laboratory (AFRL) 711 HPW/RH prepared all required documentation including a Flight Test Plan, 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).

ACKNOWLEDGEMENTS

The Army Public Health Center (APHC) and AFRL thank the 413 FLTS at Duke Field and the 96th Test Wing (TW) at Eglin AFB, FL for their support of the flight test onboard the UH-1N.

The APHC and the 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 UH-1N Iroquois helicopter located at Duke Field, Eglin AFB, 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 onboard the UH-1N 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 711 HPW/RH CBDN.

The study was a collaboration between the APHC and the AFRL, 711 (HPW), Airman Systems Directorate (RH), and was funded by the National Defense Center for Energy and Environment (NDCEE).

Two portable battery-powered data acquisition units (DAUs) were used to collect accelerations at the pilot station (right side of cockpit) and the flight engineer station (mid cabin, center). Triaxial accelerometer packs were attached to the seat base of the pilot seat and to the floor beneath the flight engineer seat. Triaxial acceleration pads were placed on top of the seat pan and seat back cushions at the pilot station, and on top of the seat pan and bulkhead at the flight engineer station. 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 test conditions, including ground operations, takeoff, hover flight, flight maneuvers, and approach. The flight engineer 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). 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 assessing the ISO 2631-1 comfort reactions, the overall vibration total values (*oVTVs)* were calculated as the vector sum of the seat pan and seat back *pVTV*s. At the flight engineer station, the occupant's seat back was the bulkhead. Therefore, the seat pan *pVTV* for health was also used to assess comfort reaction.

Most data showed a small spectral peak between 5 and 6 Hz associated with the propeller rotation frequency (PRF) of the UH-1N. The next higher peak occurred between 10.5 and 11 Hz and was associated with the blade passage frequency (BPF or 2 x PRF). Additional notable peaks were also observed at multiples of the BPF. Based on the overall vibration total values at the two stations, comfort reactions primarily ranged from "a little uncomfortable" to "uncomfortable" (ISO 2631-1) at the pilot station, and ranged from "a little uncomfortable" to "fairly uncomfortable" at the flight engineer station. Using the seat pan *pVTV*s for health at the flight engineer station, the comfort reactions ranged from "not uncomfortable" to "a little uncomfortable". Based on the seat pan *pVTV*s for health at level flight, the pilot showed the potential for health risk for daily flights lasting less than 8 hours regardless of airspeed, and in as little as 2 to 3 hours at the highest airspeed. The pilot showed no likely health risks for daily flights lasting less than 8 hours. The flight engineer was exposed to the potential for health risk

for daily exposures exceeding 8 hours (9 – 18 hours) but showed no likely health risks for daily exposures within a 24-hour period. 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 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.

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 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 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). 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; MIL-STD-1472G, 2012). Health risk and comfort assessments have been conducted on a limited number of platforms (Smith, 2005; Smith & Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008). With regard to rotary-wing aircraft, a study was conducted in 2013 to collect and assess vibration exposures onboard the HH-60M Medevac and UH-72 Lakota located at the Vermont Army National Guard (VT ARNG) (Smith, Chervak, & Steinhauer, 2014). The APHC, National Guard Bureau (NGB), and the Air Force Research Laboratory, Airmen Systems Directorate (711 HPW/RH) conducted the study. The equipment and methodology established by the AFRL 711 HPW/RH for collecting and analyzing the actual multi-axis measurements at various occupant stations were used to characterize and compare the vibration during different flight conditions, and conduct the comfort and health risk assessments in accordance with the existing standards. An aircrew questionnaire, developed by the APHC and the AFRL 711 HPW/RH, was distributed to aircrew members at the VT ARNG. The health risk assessment suggested that certain aircrew may be subjected to potential health risks in less than three hours for occupational exposures (Smith, Chervak, & Steinhauer, 2014). The AFRL 711 HPW/RH has also used these data to recreate the actual stressor environment in controlled laboratory testing for evaluating seat component influences, physiological responses, task performance, and task workload during simulated prolonged exposures.

This test program is an expansion of the previous studies conducted on rotary-wing/tilt-rotor aircraft and was funded by the NDCEE. In addition to the UH-1N, flight tests have been completed on the UH-60L, CH-47F, and MH-65D. Technical reports have been generated summarizing the results of the flight tests conducted onboard the UH-60L (Smith, Chervak, & Clasing, 2019), MH-65D (Smith & Chervak, 2019), and CH-47F (Smith & Chervak, 2020), similar to the report generated on the HH-60M and UH-72. The test program includes the development of a database quantifying operational vibration and active aircrew subjective perceptions, and integrated into the Air Force CBDN managed by the AFRL 711 HPW/RH. The database available to Department of Defense 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 onboard the UH-1N 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 CBDN.

The primary metric being measured to characterize the vibration is the acceleration generated at the human/equipment interfaces in the three orthogonal axes. This may also include the measurement of triaxial accelerations at the helmet for selected aircrew. The accelerations collected at the interfaces are frequency weighted for estimating the health risk and comfort reactions using guidelines provided in the standards.

A Memorandum of Agreement (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 Flight Test Plan, 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 discomfort and health risk assessments conducted on the UH-1N. The UH-1N was the last of the aircraft tested under the expanded flight test program funded by NDCEE.

3.0 METHODS AND PROCEDURES

3.1 Aircraft and Measurement Locations

The UH-1N (tail number 96617) is owned and operated by the 413 FLTS at Duke Field, Eglin AFB, FL. The 96th Test Wing (TW) was the Lead Development Test Organization (LDTO) for this effort. The APHC and 711 HPW/RH were Participating Test Organizations (PTOs) for the UH-1N effort. The measurement locations targeted included the pilot station located on the right side of the cockpit, and the flight engineer station located in the center cabin facing forward. All measurement stations were occupied during data collection.

3.2 Equipment, Instrumentation, and Measurement Sites

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

1. A 16-channel data acquisition unit (DAU) (Large or Small)
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

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 and measurement sites targeted for data collection, including the type of instrumentation. The table also includes the data file designation used in the CBDN.

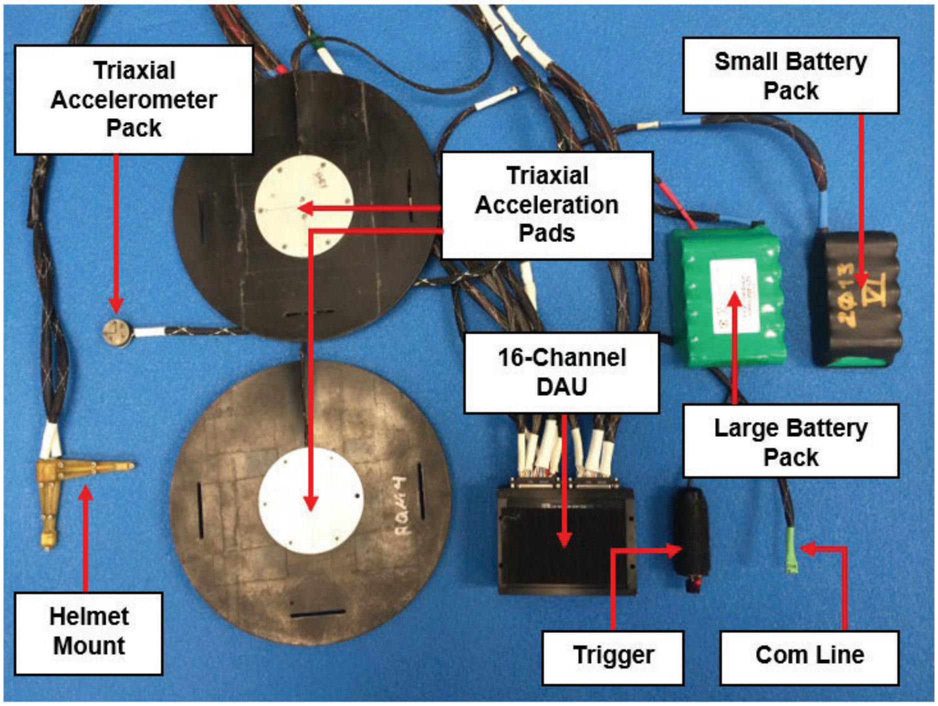

Figure 1. Remote Vibration Environment Recorder (REVER)

Table 1. UH-1N Stations/Locations, Measurement Sites, and Type of Sensors

Station	Measurement Site	Instrumentation
Pilot Station (Right Side Cockpit) CBDN Test: UH1NPILOT	Seat Base	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
	Helmet	Triaxial Accelerometer Pack
Flight Engineer Station (Mid Cabin, Center) CBDN Tests: UH1NFE	Floor Beneath Seat	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Rigid Back (Bulkhead)	Triaxial Acceleration Pad

At the pilot station, the acceleration pads were attached to the seat pan and seat back as shown in Figure 2. Figure 3 shows the mounting of the accelerometer pack beneath the seat onto the seat base.

An accelerometer pack was attached to the top of the pilot helmet as shown in Figure 4. The helmet cable was run with the communication cable using cable extensions and secured to the lower left side of the seat.

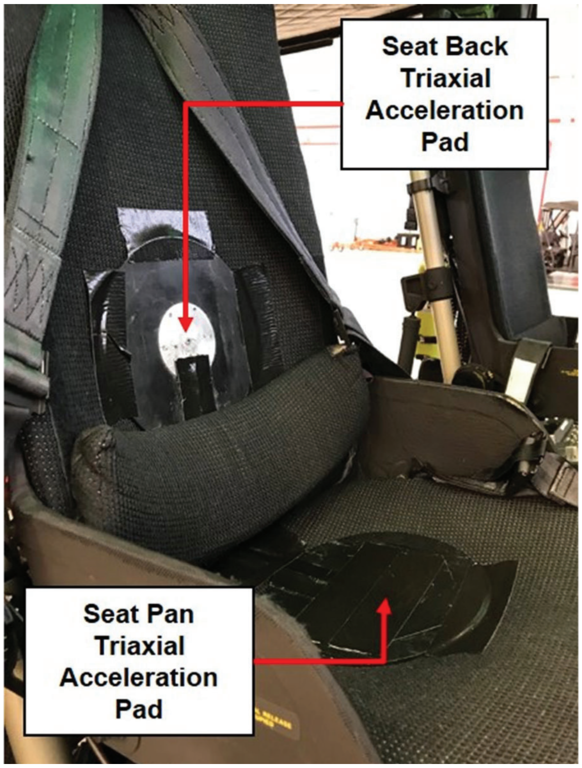

Figure 2. Pilot Seat Pan/Back Acceleration Pads

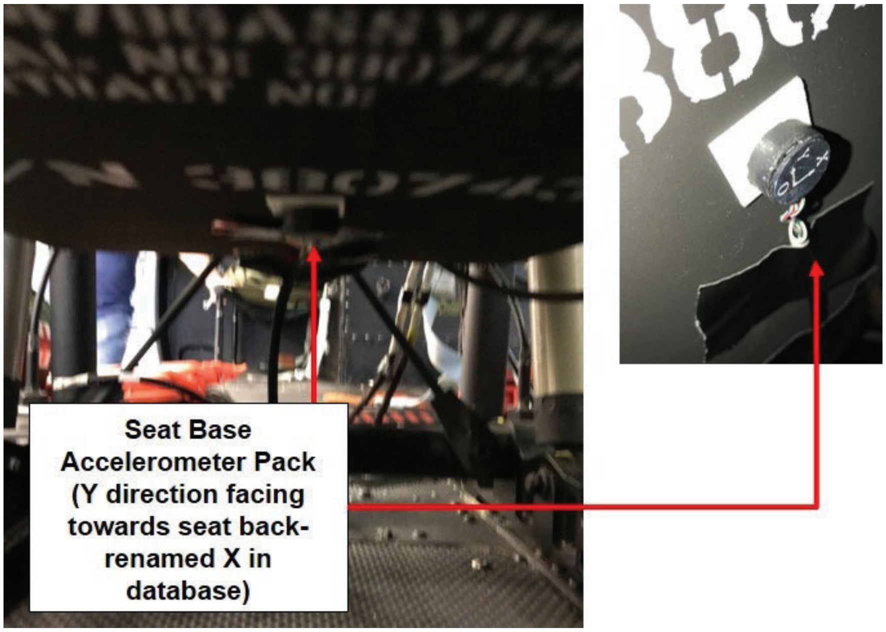

Figure 3. Pilot Seat Base Accelerometer Pack

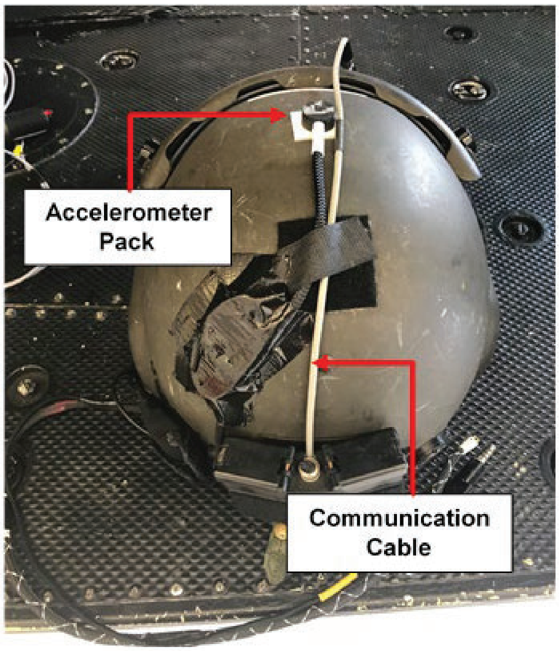

Figure 4. Pilot Helmet Configuration

At the flight engineer station, there was only a seat pan located against the aft bulkhead. The acceleration pads were attached to the seat pan and to the bulkhead as shown in Figure 5. Figure 5 also shows the mounting of the accelerometer pack to the floor beneath the seat pan.

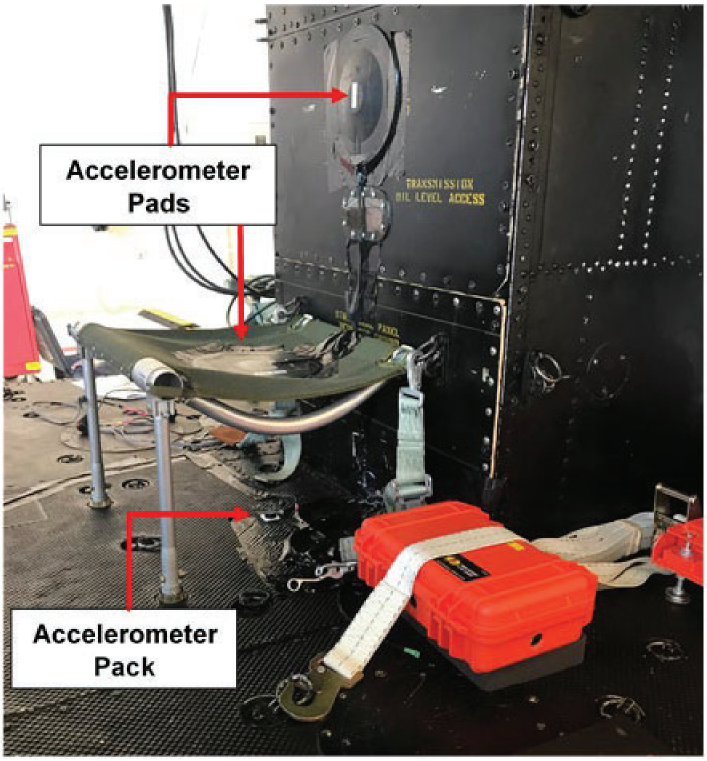

Figure 5. Flight Engineer Seat

At both stations, one DAU and two battery packs (1 small, 1 large) were contained in a Pelican case and secured with duct tape as illustrated in Figure 6. Cables were routed through holes in the case.

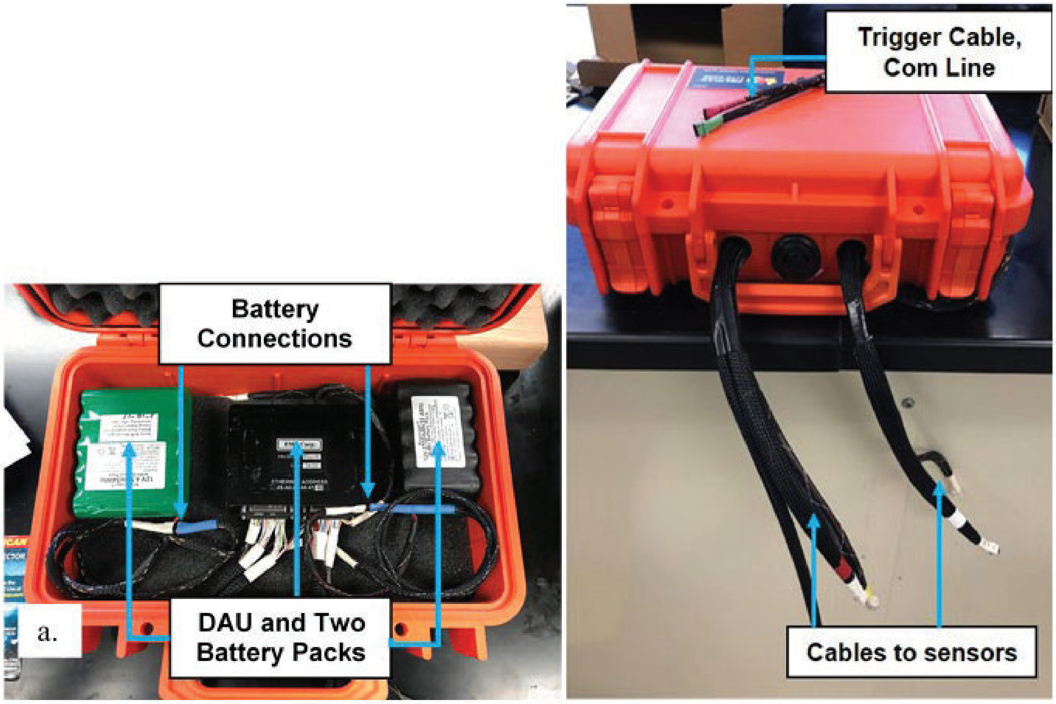

Figure 6. Pelican Case with DAU and Battery Packs

Figure 7 illustrates the location of the Pelican case associated with the pilot station. All sensor cables were routed to the DAU cables and secured to the floor with duct tape. 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. Figure 5 includes the Pelican case associated with the flight engineer station.

The triggering device (Figure 1) from each DAU was run via cable to the flight engineer 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. 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.

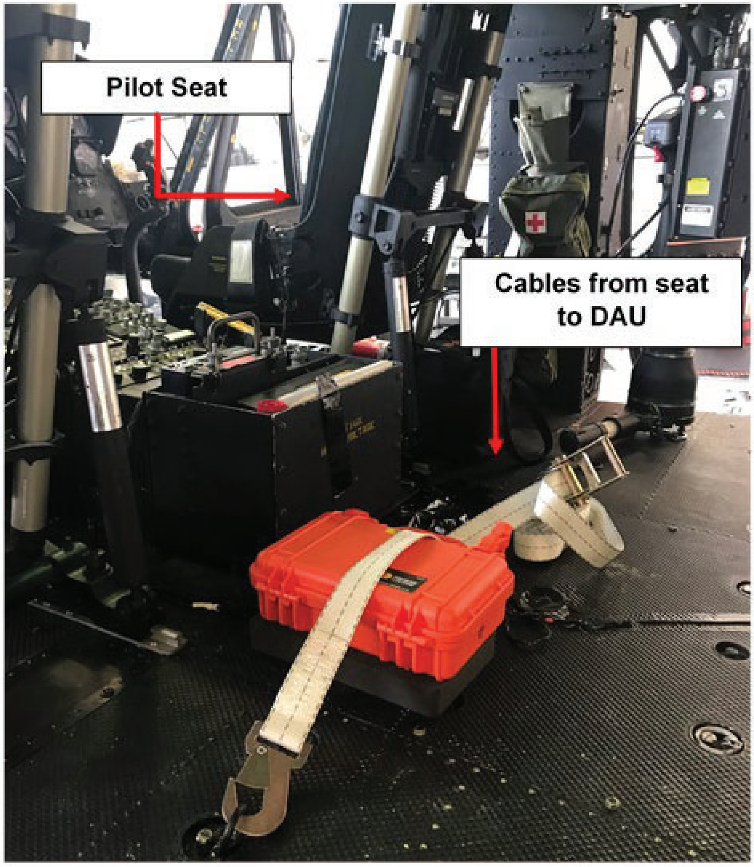

Figure 7. Pelican Case Association with Pilot Station

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. The flight test conditions were organized relative to the specific flight tasks that were identified by the aircrew. The flight engineer triggered data collection for both targeted stations 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 as annotated in Table A-2. Data records were collected throughout the flight and not necessarily collected in the order presented in Table A-2. The flight engineer 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.

3.3.2. Data Processing and Analysis

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 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 the two UH-1N stations at the floor or seat base, seat pan, seat back, and helmet (pilot only).

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

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 (W) and multiplying factors (k) listed in Table 2, based on human sensitivity to the location, frequency, and direction of vibration, were used to assess comfort reaction and health risk. Figure 8 illustrates W for the respective locations and directions as listed in Table 2.

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

	HEALTH RISK Seat Pan		COMFORT REACTION Seat Pan		COMFORT REACTION 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	$k = 0.4$

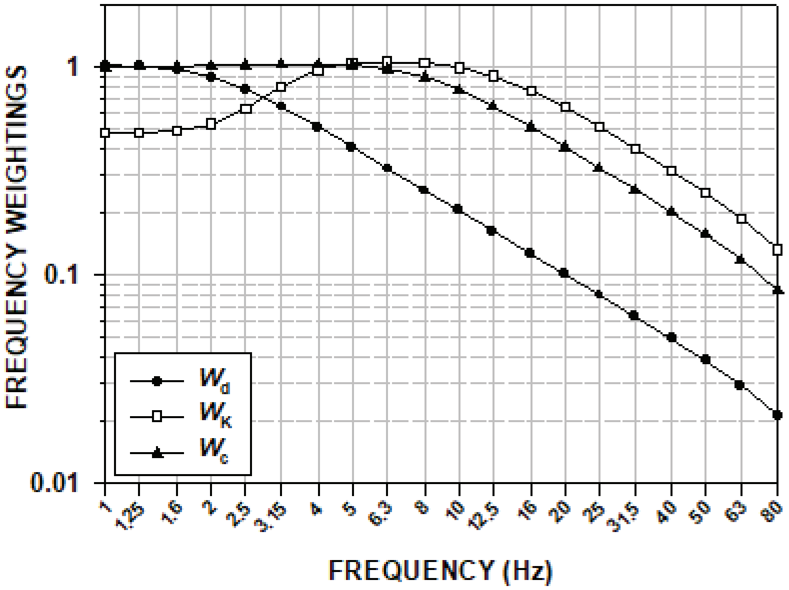

Figure 8. ISO 2631 Frequency Weightings W_d, W_k, and W_c (ISO 2631-1: 1997)

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:

$$a_w \;=\; \left[\sum W_{ij}^2 a_{rmsi}^2\right]^{1/2} \tag{2}$$

where W_{ij} 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 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 location):

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

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. 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 (see below). 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) illustrated in Figure 9 (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

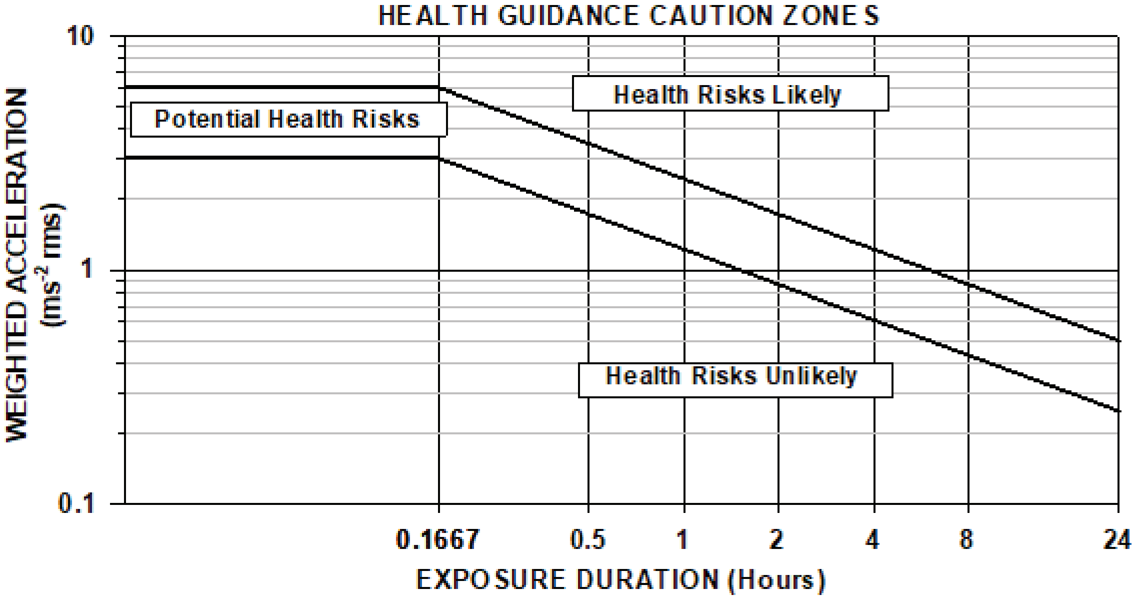

Figure 9. ISO 2631-1 Health Guidance Caution Zones (HGCZs)

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 states the following:

> *"For exposures lasting 8.0 hours or less, the seat pan frequency weighted triaxial RMS accelerations in any orthogonal direction* (or *pVTV*) *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"*

A revision of the MIL-STD-1472 (version H) is scheduled for release in 2020 that may include modifications to these exposure criteria.

4.0 RESULTS

All Figures and Tables referred to in this section are located in the Appendix. A total of 105 records were collected for the UH-1N flight test conditions listed in Table A-2.

4.1 Characteristics of the Multi-Axis Accelerations Onboard the UH-1N

4.1.1. UH-1N Acceleration Spectra

Typically, with helicopters, a peak in the acceleration spectra is expected to 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. A peak is also expected to occur at the blade passage frequency or BPF, which is predicted as the number of blades multiplied by the PRF. This peak tends to be the highest in magnitude but does depend on the flight condition and aircraft. Both the PRF and BPF may vary slightly depending on the flight maneuver and whether the aircraft is operated at 100% power. Additional peaks are 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 and A-2 illustrate sample acceleration spectra for the UH-1N at the seat base or floor, seat pan, seat back or rigid seat back (bulkhead), and helmet (pilot only) in the fore-and-aft (X), lateral (Y), and vertical (Z) directions for a selected data record collected during level flight (100 KIAS) at the pilot and flight engineer stations, respectively. Most flight data showed a small peak between 5 and 6 Hz, typically at 5.5 Hz, that was associated with the PRF of the aircraft. The next higher peak occurred between 10.5 and 11 Hz and was associated with the BPF (2 x PRF). All measurement locations showed additional peaks at multiples of the BPF. Interestingly, as shown in Figures A-1 and A-2, the highest peak did not always occur at the BPF, but at a multiple of the BPF depending on the occupant station, measurement site, and direction. It is not clear what contributed to peaks observed at other frequencies. In addition, while the peak at the PRF tended to be the highest in the vertical (Z) direction at the seat/occupant interfaces, particularly at the pilot station, this was not necessarily the case at subsequent peaks observed at the BPF and multiples of the BPF (also see Section 3.3.2 regarding the overall unweighted accelerations during level flight). It is interesting that the highest peaks occurring at the pilot helmet at the PRF and BPF were consistently observed in the lateral (Y) direction, although the head orientation can affect the results. As expected, vibration beyond the BPF was dampened at the helmet. In addition, the relatively high levels of higher frequency vibration at the flight engineer back interface was most likely influenced by the response of the metal bulkhead.

4.1.2. Overall Unweighted Accelerations

Figures A-3 and A-4 illustrate the mean unweighted overall accelerations ± one standard deviation between 1 and 80 Hz at the seat base or floor, seat pan, and seat back measurement sites, in each direction, for each flight test condition, at the pilot and flight engineer stations, respectively. Tables A-3 and A-4 include the unweighted overall seat pan accelerations for each level flight record at each of the two aircrew stations, respectively. In general, both stations showed overall accelerations for level flight that tended to be similar to the overall accelerations observed for the other flight test conditions, with a few exceptions.

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 seat base or floor, seat pan, seat back, and helmet (pilot only) during level flight at the three airspeeds. Significant differences were associated with $P<0.05$. The results are listed in Table A-5. At the pilot station, the seat base overall unweighted vertical (Z) accelerations tended to be the highest, while the seat base fore-and-aft (X) accelerations were the lowest at all three airspeeds (Figure A-3, Table A-5). In contrast, the pilot seat pan overall unweighted fore-and-aft (X) accelerations were the highest, with mixed results in the lateral (Y) and vertical (Z) directions (Figure A-3, Table A-5). At the pilot seat back, the lateral (Y) accelerations tended to be the lowest, with mixed results in the fore-and-aft (X) and vertical (Z) directions (Figure A-3, Table A-5). As mentioned, these trends tended to similar for the other flight test conditions. As described for the peak accelerations at the pilot helmet, the unweighted overall accelerations at the helmet were highest in the lateral (Y) direction (Table A-7).

At the flight engineer station, the overall unweighted floor vertical (Z) accelerations were the highest and the fore-and-aft (X) accelerations were the lowest (Figure A-4, Table A-5). In contrast, the flight engineer seat pan overall unweighted fore-and-aft (X) accelerations were the highest at the three airspeeds (Figure A-4, Table A-5). At the flight engineer seat back, the overall unweighted vertical (Z) accelerations tended to be the highest, while the lateral (Y) overall unweighted accelerations tended to be the lowest. Again, these trends were similar among the other flight test conditions. The relatively higher overall unweighted vertical (Z) accelerations at the seat back may have been influenced by higher frequency vibration being transmitted to the bulkhead as illustrated in Figure A-2 for the seat back spectra.

The effect of airspeed was not statistically evaluated for the overall unweighted accelerations. For both stations, there appeared to be no clear trend in the overall levels with increasing airspeed.

4.2 Assessment of the UH-1N 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 overall unweighted accelerations at the floor or seat base, seat pan, and seat back, and the overall weighted accelerations at the seat pan and seat back at the two aircrew stations are provided in Figure A-5 for comparison. The figure also includes plots of the *pVTV*s and *oVTV* for the comfort assessment, and the *pVTV*s for health risk assessment. All plots include the mean overall unweighted or weighted accelerations combined for level flight at the three airspeeds. The figure shows the higher overall unweighted fore-and-aft (X) accelerations measured at the seat pan for the two stations (Figure A-5, blue bars) as illustrated in Figures A-3 and A-4. However, the highest overall weighted seat pan accelerations occurred in the vertical (Z) direction at both stations (Figure A-5, yellow bars). This difference was dramatic for both stations even with the 1.4 multiplying factor applied to the horizontal directions in accordance with Table 2 for assessing health risk. It is noteworthy that the frequency weighting, W_d, for the horizontal directions reduce the higher frequency contributing accelerations to a much greater extent than in the vertical direction (W_k) (Figure 8). Likewise, Figure A-5 shows a tendency for higher overall unweighted vertical (Z) accelerations measured at the seat back for both stations (blue bars) as illustrated in Figures A-3 and A-4 and as listed in Table A-5. However, the highest overall weighted seat back accelerations occurred in the fore-and-aft (X) direction for both aircrew stations (Figure A-5, yellow bars). The multiplying factors and frequency weightings also affected the contributions at the seat back (Table 2, Figure 8).

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 the two aircrew 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 Eq. (3) and using the frequency weightings and multiplying factors in Table 2. As described previously, the assessment of comfort reactions at the flight engineer station also included the seat pan *pVTV* using the 1.4 multiplying factor for assessing health risk in the horizontal directions, in accordance with ISO 2631-1. The Comfort Reactions are independent of time.

Figure A-6 plots the *oVTV*s at the pilot station and Figure A-7 plots both the *oVTV*s and seat pan *pVTV*s at the flight engineer station for assessing comfort reaction for all flight test conditions. All figures include illustration of the ISO 2631-1 Comfort Reactions. Figure A-6 shows that the pilot *oVTV*s ranged from being considered “a little uncomfortable” to “uncomfortable” during flight, with a majority of the flight conditions being considered “fairly uncomfortable”. Figure A-7 shows that the comfort reactions at the flight engineer station, based on the *oVTV*s, were considered “a little uncomfortable” to “fairly uncomfortable” during flight. The comfort reactions based on the *pVTV*s for health risk were less uncomfortable, ranging from “not uncomfortable” to “a little uncomfortable” for most flight test conditions. It was not clear if the back of the flight engineer was in contact with the bulkhead during all measurements.

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. The health risk assessment is dependent on the daily exposure duration. It was assumed that the range of accelerations collected at 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 and A-4 list the weighted overall seat pan accelerations and seat pan *pVTV*s for assessing health risk for each level flight record at the pilot and flight engineer stations, respectively. The tables also list the minimum exposure duration for each listed record, in hours, for potential health risk (lower boundary of HGCZs) and minimum exposure duration for likely health risks (upper boundary of HGCZs) (Figure 9). These exposure durations were based on the highest overall seat pan acceleration 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, regardless of the station, as noted in the summary plots illustrated in Figure A-5 and Tables A-3 and A-4. 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 maneuvers and records would reach the two boundaries in less than 8 hours.

Figure A-8 illustrates the minimum exposure durations associated with the potential for health risk at the two aircrew stations at each airspeed based on the seat pan *pVTV*s. Figure A-9 illustrates the minimum exposure durations associated with likely health risks. Both figures indicate that, based on the *pVTV*, lower durations occurred at the higher airspeeds for the seated aircrew. These durations were associated with the tendency for higher seat pan *pVTV*s at higher airspeeds.

In summary, based on the *pVTV*s, the pilot was exposed to the potential for health risk in less than eight hours for all measured acceleration levels at the three airspeeds (Figure A-8, Table A-3, highlighted in orange). At Velocity Never to Exceed (V_{NE})-5 KIAS, the pilot potential for health risk existed in as little as 2 to 3 hours of daily flight. Likely health risks for the pilot were associated with daily durations of 8 hours and greater, regardless of airspeed.

Based on the *pVTV*s, the flight engineer was exposed to the potential for health risk in greater than 8 hours of daily flight at all airspeeds, with the shortest durations associated with the highest airspeed. At the highest airspeed, the potential for health risk occurred within 9 to 18 hours of daily flight (Table A-4). Likely health risk for the flight engineer were not expected based on daily exposures within a 24-hour period (Table A-4).

5.0 DISCUSSION AND CONCLUSIONS

This document provides a summary of the vibration exposure characterization and assessment conducted onboard the UH-1N helicopter. Included is a synopsis of the seat pan and seat back acceleration spectra generated by the aircraft. The characteristics of the spectra generated by the UH-1N were similar to that observed during other investigations conducted on rotary-wing and tilt-rotor aircraft, where the highest accelerations were associated with the propulsion system and occurred at relatively distinct frequencies (Smith, 2005; Smith & Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008; Smith, Chervak, & Steinhauer, 2014; Smith, Chervak, & Clasing, 2019; Smith & Chervak, 2019; Smith & Chervak, 2020). A relatively smaller peak associated with the propeller rotation frequency or PRF was observed below 10 Hz. A peak in the spectra was also observed between 10.5 and 11.0 Hz and associated with the blade passage frequency or BPF. Additional and substantial peaks were observed at harmonics of the BPF for the UH-1N.

The consistency in the directional effects among the flight test conditions illustrated in Figures A-4 and A-5 at the various measurement sites was of particular interest. Both the pilot seat base overall unweighted accelerations (measured near the floor) and the flight engineer floor overall levels were notably the lowest in the fore-and-aft (X) direction but the highest at the seat pan. This may be influenced by the location of the pilot station and the flight engineer station relative to the rotating blades. The pilot is located quite a bit forward and left of the rotor, while the flight engineer is located slightly forward of the rotor.

As shown in Figure A-5, the higher frequencies associated with the UH-1N, as with other rotary-wing/tilt-rotor aircraft, can be substantially weighted once the ISO 2631-1 frequency weightings and multiplying factors are applied for calculating the overall weighted accelerations, *pVTVs*, and *oVTVs*. This is particularly true for the horizontal vibration measured at the seat pan, and the lateral and vertical vibration measured at the seat back. This can dramatically reduce the contribution of the vibration to the comfort reaction and health risk assessments defined in the standards. Regardless, as with other rotary-wing/tilt-rotor aircraft, the UH-1N did show that certain flight test conditions were associated with seated comfort reactions ranging from being considered 'a little uncomfortable' to 'uncomfortable', particularly at the pilot station, as illustrated in Figure A-5. The aircraft also showed level flight exposures associated with the potential for health risk in less than 8 hours, and like health risks in greater than 8 hours at the pilot station, as illustrated in Figures A-8 and A-9, and Table A-3. However, the level flight exposures at the flight engineer station, located in the center of the aircraft, showed no potential for health risk or likely health risk in 8 hours or less, as illustrated in Figures A-8 and A-9, and Table A-4. At higher airspeeds, the UH-1N exposed the pilot to higher *pVTV*s associated with lower exposure durations, similar to what has been observed on other rotary-wing platforms.

Figure 10 compares the seat pan *pVTV*s from all aircraft that have been assessed for health risk in accordance with ISO 2631-1 and were part of the Army and Air Force collaboration. With the exceptions of the UH-72 Crew Chief station and the UH-1N Flight Engineer Station, of the tested aircraft have shown the potential for health risk in less than 8 hours of daily occupational exposures to level flight.

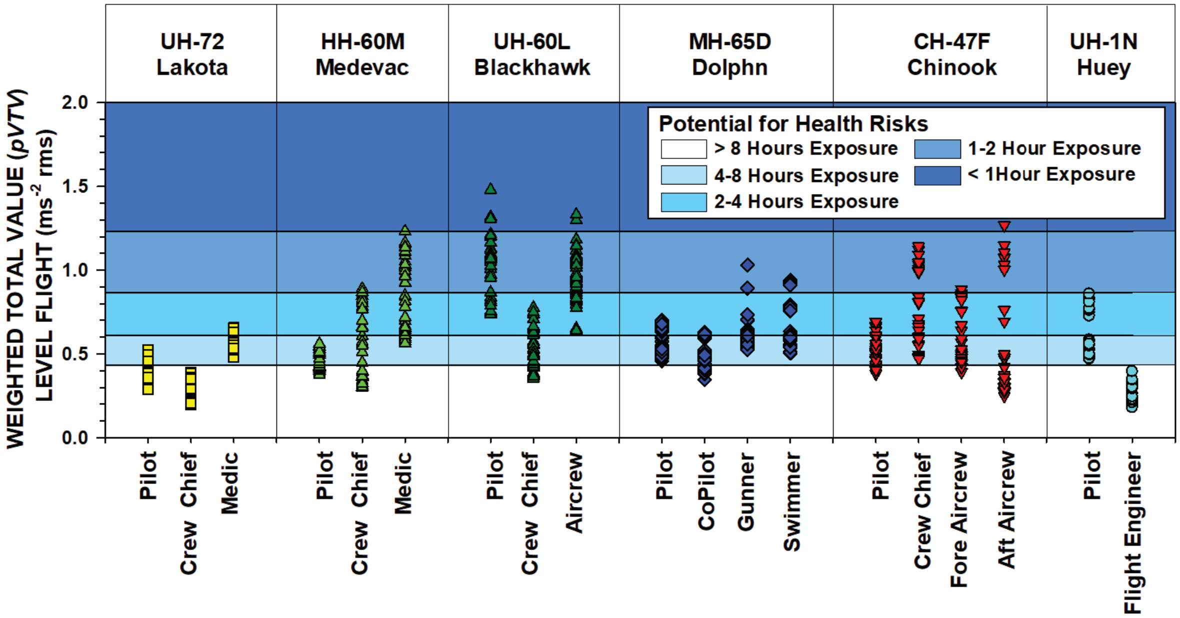

Figure 10. Comparison of Health Risk *pVTVs* Among Rotary-Wing/Tilt -Rotor Aircraft

In summary, the results of the assessments on the UH-1N 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, leading to the development of more robust discomfort and pain mitigation strategies.

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APPENDIX: RESULTS – FIGURES AND TABLES

LIST OF FIGURES

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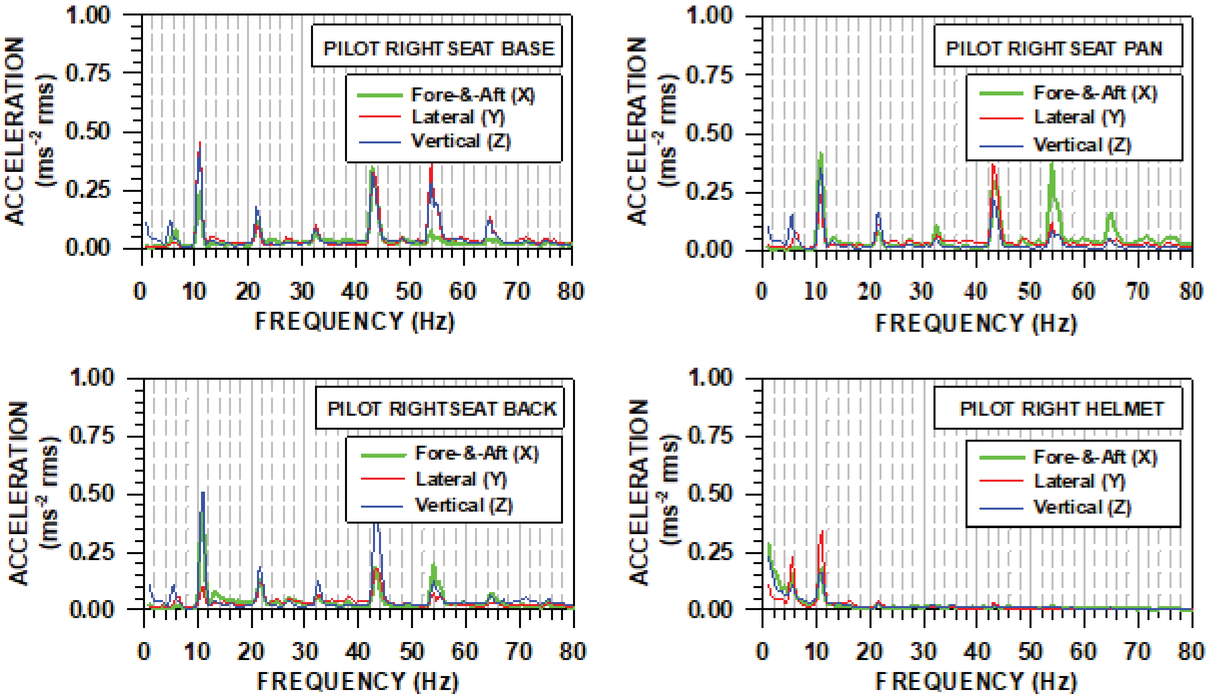

Figure A- 1. Sample Acceleration Spectra at Level Flight (100 KIAS) at the Pilot Station

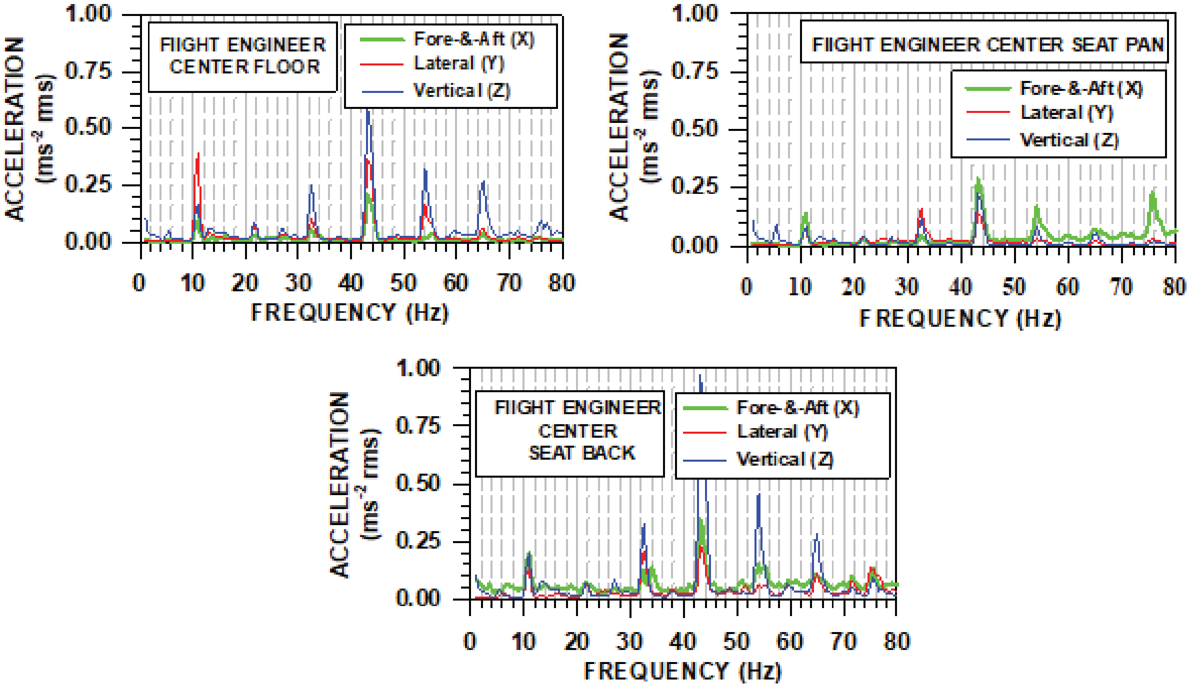

Figure A- 2. Sample Acceleration Spectra at Level Flight (100 KIAS) at the Flight Engineer Station

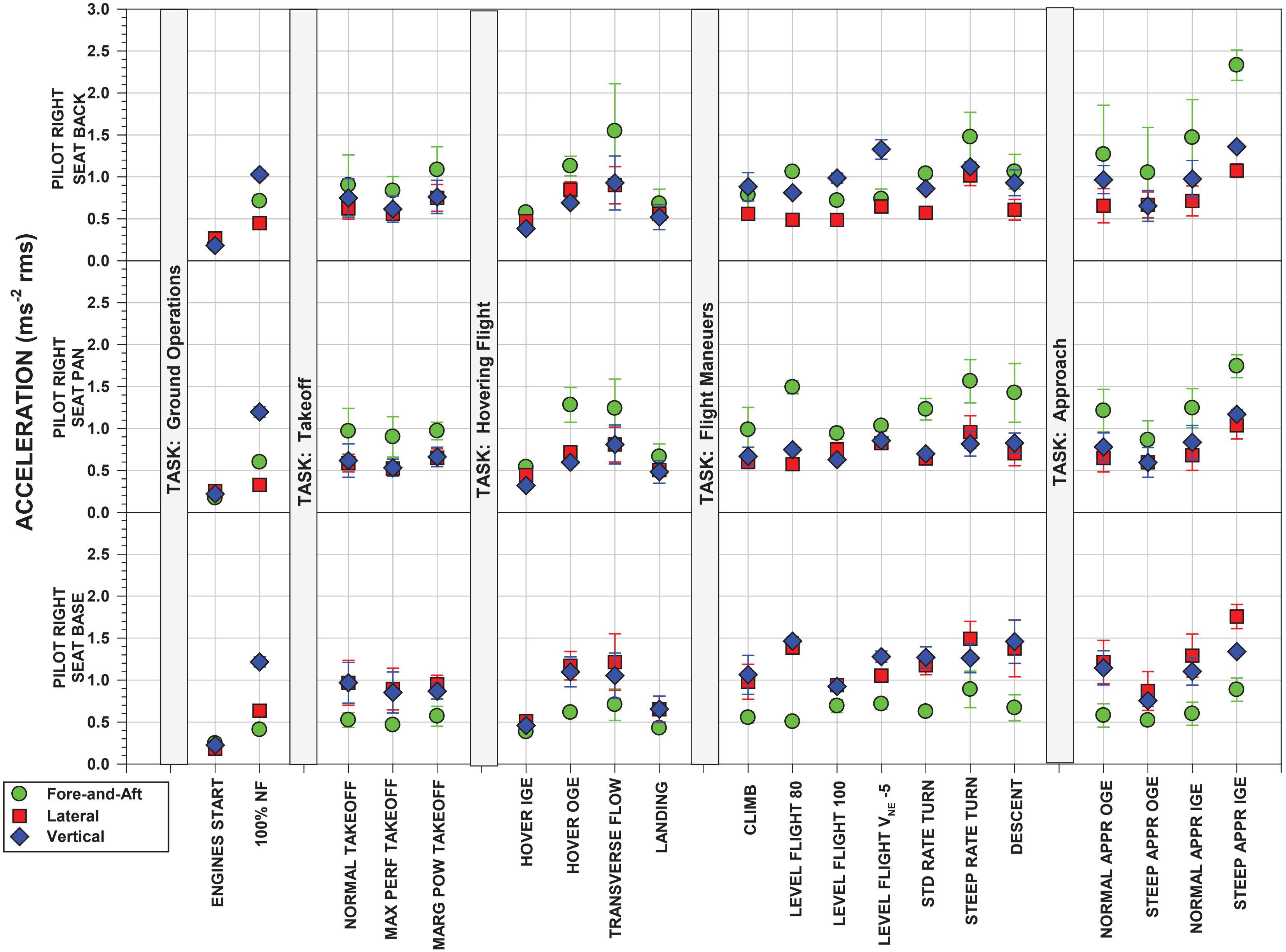

Figure A- 3. UH-1N Pilot **Mean Overall Unweighted Accelerations ± One Standard Deviation**

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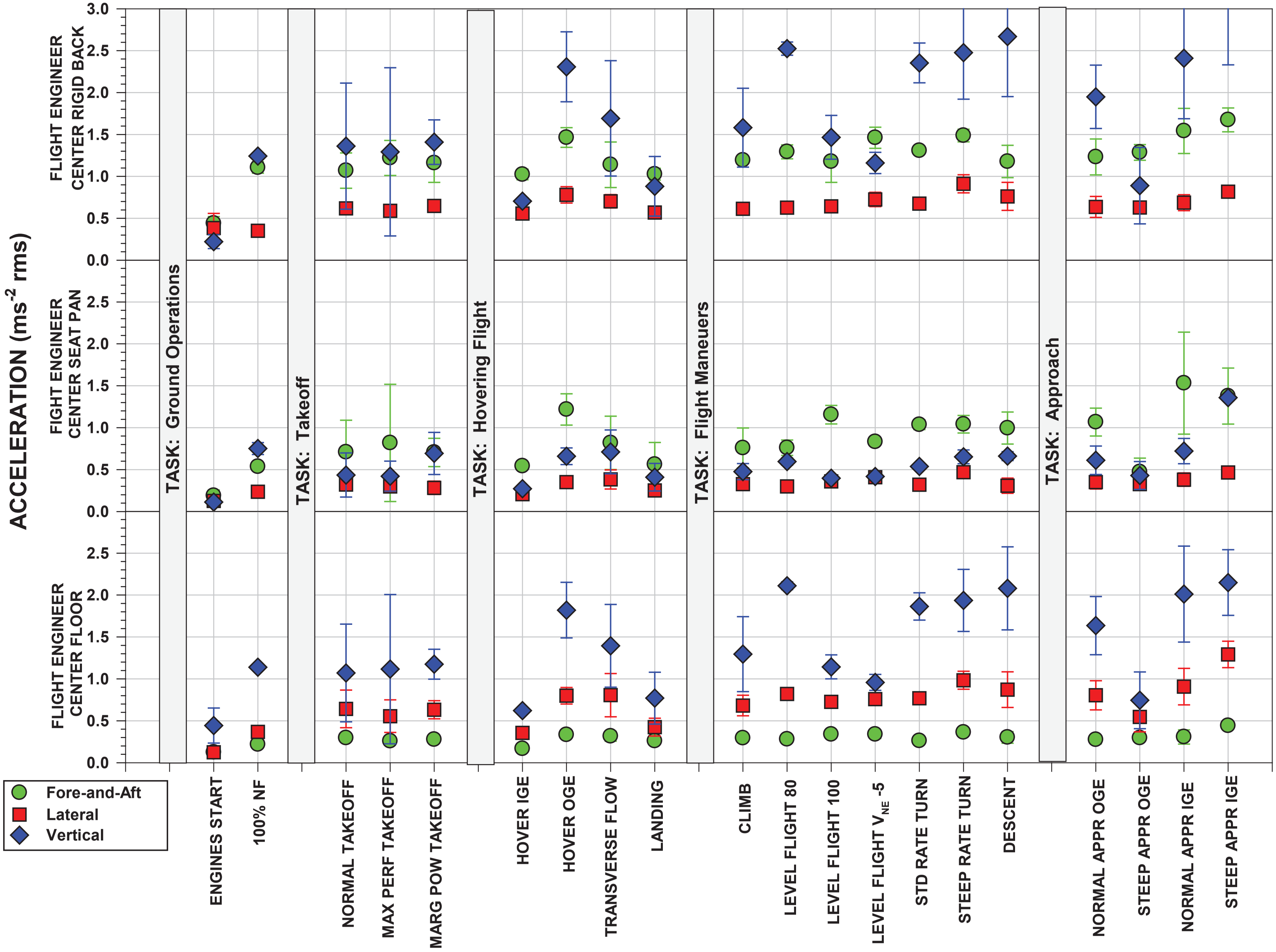

Figure A- 4. UH-1N Flight Engineer Mean Overall Unweighted Accelerations ± One Standard

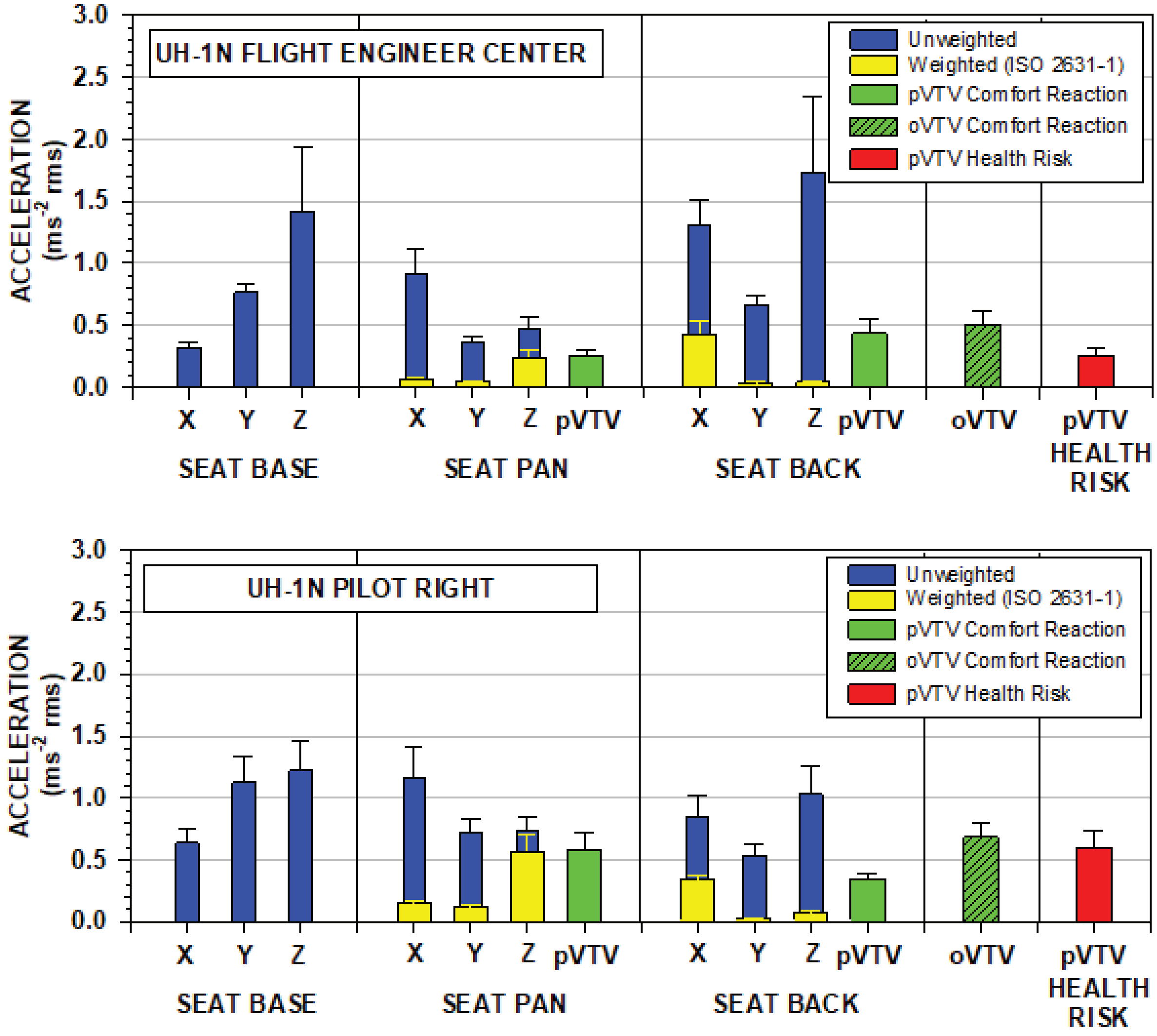

Figure A- 5. UH-1N Mean Unweighted and Weighted Overall Accelerations, *pVTV*s, and *oVTV*s ± One Standard Deviation

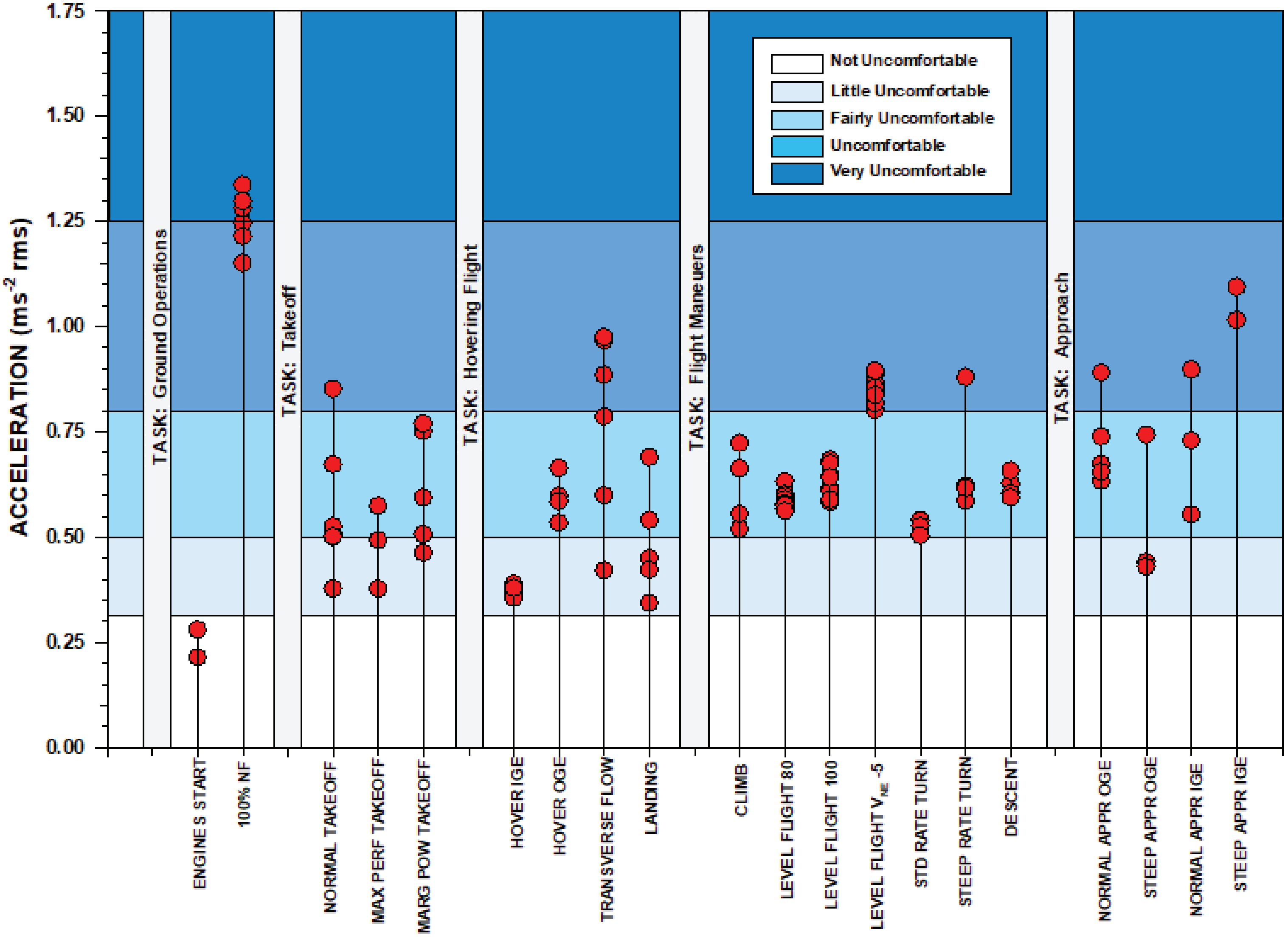

Figure A- 6. UH-1N Pilot Station *oVTV*s

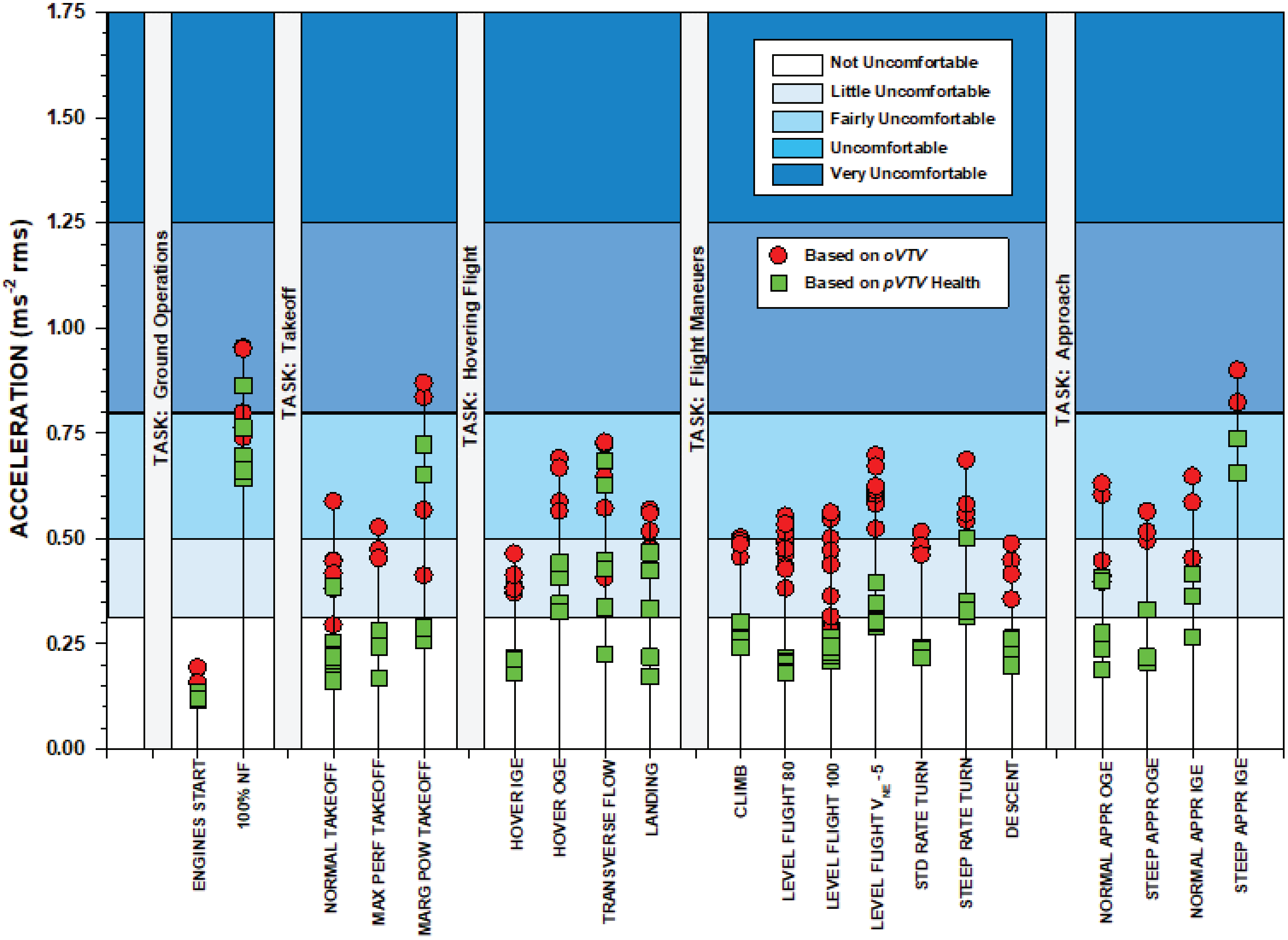

Figure A- 7. UH-1N Flight Engineer Station *oVTVs* and Seat Pan *pVTVs* for Health Risk

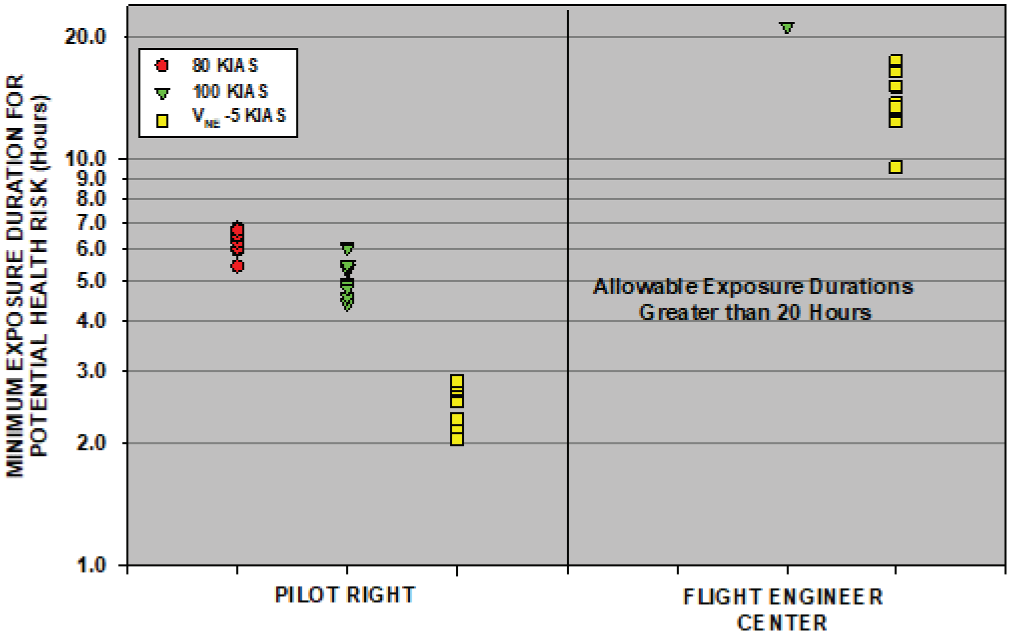

Figure A- 8. UH-1N Level Flight Minimum Exposure Duration for "Potential Health Risk" in a 24-Hour Period (ISO 2631-1)

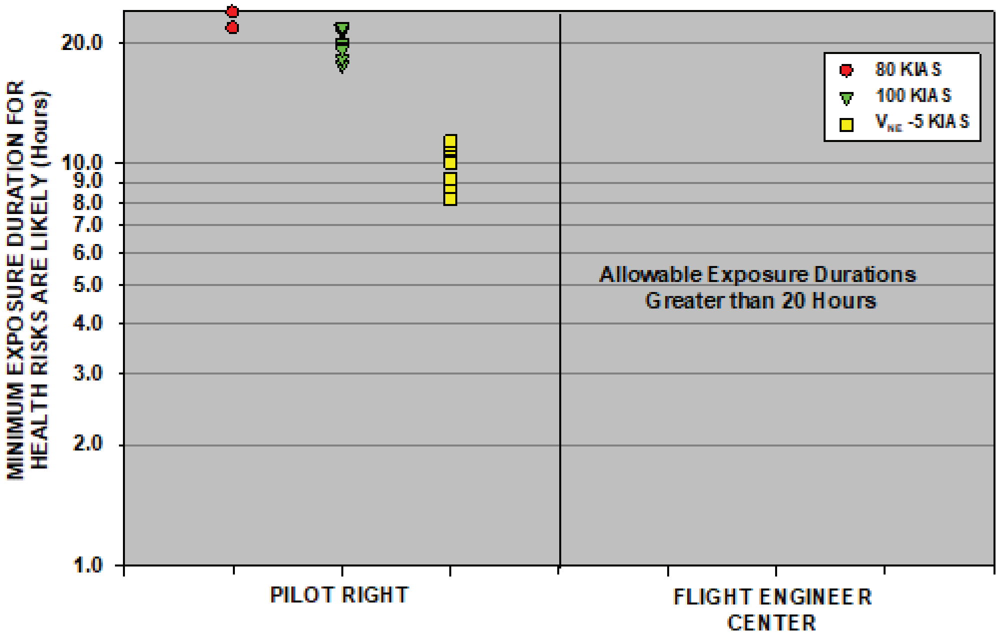

Figure A- 9. UH-1N Level Flight Minimum Exposure Duration for "Health Risks Likely" in a 24-Hour Period (ISO 2631-1)

Table A- 1. REVER Component Details

Component	Dimensions (L/W/H cm)	Weight (Kg)	Item Identification
Small DAUs	9.5/7.0/2.8	0.370 w/cables	EME S/N 04-22 EME S/N 10-31
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 AD Pack AE Pack AA
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
Extra Cable	183 (length)	0.100	
Total estimated weight w/ two batteries + cable and two acceleration pads		2.23 – 2.77	

Table A- 2. UH-1N Flight Tasks and Flight Test Condition Records

Task/Condition	# of Records	Bad Records
TASK: GROUND OPERATIONS		
Engine(s) Start Idle	3	0
Ground Flight 100% Nf	6	0
TASK: TAKEOFF		
Normal Takeoff	7	0
Max Performance Takeoff	3	0
Marginal Power Takeoff	5	0
TASK: HOVER FLIGHT		
Hover IGE	5	0
Hover OGE	4	0
Transverse Flow	6	0
Landing (hover)	5	0
TASK: FLIGHT MANEUVERS		
Climb	4	0
Descent	4	0
Level Flight 80 KIAS	11	0
Level Flight 100 KIAS	11	0
Level Flight V_{NE}-5 KIAS	10	0
Standard Rate Turn	4	0
Steep Rate Turn	4	0
TASK: APPROACH		
Normal Approach to OGE	5	0
Steep Approach to OGE	3	0
Normal Approach to IGE	3	0
Steep Approach to IGE	2	0

KIAS: Knots Indicated Airspeed
IGE: In Ground Effect
OGE: Out of Ground Effect
Nf: = Free Turbine Speed
V_{NE}-5: Velocity Not to Exceed – 5 KIAS

Table A- 3. UH-1N 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 (KIAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	pVTV	POTENTIAL HLTH RISKS WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISKS PAN pVTV	HLTH RISKS LIKELY PAN pVTV
			ACCELERATION (ms $^{-2}$ rms)							EXPOSURE DURATION (Hours)			
1	80	35	1.609	0.625	0.794	0.162	0.104	0.488	0.525	6.291	25.163	5.443	21.770
1	80	36	1.589	0.571	0.773	0.155	0.099	0.467	0.502	6.883	27.530	5.962	23.847
1	80	37	1.557	0.566	0.755	0.151	0.094	0.466	0.499	6.910	27.641	6.035	24.139
1	80	38	1.490	0.542	0.743	0.148	0.092	0.451	0.483	7.373	29.491	6.418	25.671
1	80	39	1.538	0.584	0.754	0.149	0.091	0.458	0.490	7.164	28.657	6.253	25.012
1	80	40	1.422	0.561	0.712	0.142	0.092	0.440	0.471	7.757	31.028	6.761	27.043
1	80	41	1.496	0.618	0.740	0.149	0.094	0.443	0.477	7.646	30.583	6.602	26.408
1	80	42	1.454	0.563	0.742	0.146	0.089	0.450	0.481	7.419	29.675	6.479	25.915
1	80	43	1.468	0.559	0.747	0.145	0.085	0.452	0.482	7.351	29.405	6.456	25.823
1	80	44	1.460	0.573	0.750	0.144	0.083	0.450	0.480	7.398	29.593	6.508	26.032
1	80	45	1.331	0.564	0.714	0.138	0.082	0.445	0.474	7.559	30.236	6.689	26.757
MEAN			1.492	0.575	0.748	0.148	0.091	0.455	0.488	7.250	29.000	6.328	25.311
STDEV			0.080	0.025	0.023	0.007	0.006	0.014	0.016	0.420	1.680	0.385	1.540
1	100	24	0.900	0.749	0.605	0.147	0.111	0.497	0.530	6.078	24.313	5.339	21.355
1	100	25	0.906	0.707	0.617	0.151	0.108	0.493	0.526	6.184	24.736	5.416	21.663
1	100	26	0.910	0.735	0.608	0.152	0.109	0.494	0.528	6.142	24.568	5.373	21.491
1	100	27	0.910	0.728	0.606	0.154	0.111	0.487	0.523	6.325	25.302	5.488	21.951
1	100	28	0.925	0.758	0.587	0.153	0.108	0.459	0.496	7.123	28.493	6.108	24.432
1	100	29	0.917	0.713	0.587	0.153	0.110	0.461	0.498	7.061	28.244	6.052	24.208
1	100	30	1.062	0.773	0.681	0.158	0.119	0.512	0.549	5.727	22.908	4.980	19.919
1	100	31	0.914	0.719	0.655	0.161	0.136	0.544	0.584	5.068	20.270	4.405	17.619
1	100	32	0.888	0.690	0.623	0.154	0.133	0.515	0.554	5.650	22.600	4.891	19.563
1	100	33	0.918	0.711	0.650	0.162	0.126	0.535	0.573	5.244	20.976	4.570	18.280
1	100	34	1.111	0.987	0.686	0.152	0.134	0.521	0.559	5.532	22.127	4.808	19.233
MEAN			0.942	0.752	0.628	0.154	0.119	0.502	0.538	6.012	24.049	5.221	20.883
STDEV			0.073	0.082	0.035	0.005	0.011	0.027	0.028	0.664	2.656	0.552	2.209
1	V_{NE}-5	46	1.137	0.853	0.896	0.169	0.146	0.801	0.832	2.336	9.342	2.168	8.671
1	V_{NE}-5	47	1.014	0.810	0.801	0.159	0.133	0.719	0.748	2.904	11.616	2.681	10.724
1	V_{NE}-5	48	1.027	0.865	0.791	0.171	0.157	0.688	0.727	3.165	12.659	2.841	11.363
1	V_{NE}-5	49	1.067	0.869	0.826	0.180	0.164	0.721	0.761	2.888	11.553	2.593	10.374
1	V_{NE}-5	50	1.018	0.809	0.829	0.169	0.155	0.734	0.769	2.784	11.135	2.535	10.142
1	V_{NE}-5	51	0.926	0.924	0.841	0.160	0.168	0.736	0.772	2.768	11.071	2.519	10.075
1	V_{NE}-5	52	0.983	0.854	0.885	0.155	0.145	0.797	0.825	2.362	9.450	2.205	8.821
1	V_{NE}-5	53	1.086	0.765	0.895	0.148	0.115	0.806	0.827	2.311	9.244	2.193	8.772
1	V_{NE}-5	54	0.993	0.716	0.869	0.142	0.122	0.788	0.810	2.414	9.656	2.286	9.142
1	V_{NE}-5	55	1.078	0.779	0.934	0.151	0.127	0.835	0.858	2.151	8.604	2.038	8.151
MEAN			1.033	0.824	0.857	0.160	0.143	0.763	0.793	2.608	10.433	2.406	9.623
STDEV			0.061	0.061	0.046	0.012	0.018	0.048	0.043	0.334	1.334	0.263	1.052

Table A- 4. UH-1N Flight Test Engineer 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 (KIAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	pVTV	POTENTIAL HLTH RISKS WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISKS PAN pVTV	HLTH RISKS LIKELY PAN pVTV
			ACCELERATION (ms $^{-2}$ rms)							EXPOSURE DURATION (Hours)			
1	80	35	0.793	0.355	0.631	0.060	0.040	0.206	0.218	35.394	141.577	31.551	126.205
1	80	36	0.653	0.328	0.612	0.060	0.041	0.202	0.215	36.667	146.668	32.493	129.971
1	80	37	0.656	0.329	0.635	0.056	0.040	0.195	0.207	39.494	157.978	35.094	140.374
1	80	38	0.797	0.328	0.616	0.065	0.036	0.189	0.203	41.993	167.973	36.432	145.729
1	80	39	0.781	0.315	0.611	0.056	0.037	0.195	0.206	39.601	158.405	35.409	141.636
1	80	40	0.815	0.312	0.607	0.055	0.035	0.194	0.205	39.826	159.302	35.823	143.292
1	80	41	0.677	0.301	0.652	0.055	0.037	0.199	0.210	37.930	151.720	34.118	136.472
1	80	42	0.860	0.294	0.576	0.067	0.040	0.188	0.203	42.440	169.759	36.230	144.921
1	80	43	0.675	0.232	0.562	0.050	0.034	0.176	0.186	48.398	193.590	43.297	173.186
1	80	44	0.728	0.244	0.541	0.049	0.033	0.172	0.182	50.716	202.863	45.352	181.410
1	80	45	0.933	0.250	0.512	0.054	0.034	0.169	0.181	52.609	210.435	45.973	183.890
MEAN			0.761	0.299	0.596	0.057	0.037	0.189	0.201	42.279	169.115	37.434	149.735
STDEV			0.091	0.040	0.043	0.005	0.003	0.012	0.013	5.781	23.123	5.046	20.184
1	100	24	1.117	0.342	0.391	0.071	0.042	0.219	0.234	31.159	124.638	27.311	109.244
1	100	25	1.070	0.342	0.391	0.071	0.046	0.213	0.230	32.909	131.636	28.441	113.762
1	100	26	1.151	0.343	0.385	0.071	0.043	0.209	0.225	34.274	137.098	29.624	118.497
1	100	27	1.221	0.346	0.375	0.071	0.041	0.205	0.221	35.594	142.375	30.696	122.786
1	100	28	1.154	0.369	0.393	0.071	0.043	0.199	0.216	37.862	151.449	32.247	128.986
1	100	29	1.097	0.373	0.393	0.067	0.043	0.196	0.211	39.243	156.974	33.711	134.842
1	100	30	1.304	0.395	0.485	0.073	0.045	0.221	0.237	30.650	122.598	26.640	106.558
1	100	31	1.040	0.347	0.361	0.104	0.068	0.234	0.265	27.394	109.576	21.394	85.575
1	100	32	0.978	0.357	0.340	0.069	0.043	0.209	0.224	34.434	137.736	29.844	119.378
1	100	33	1.241	0.347	0.382	0.073	0.048	0.213	0.231	32.926	131.705	28.180	112.720
1	100	34	1.334	0.392	0.464	0.077	0.042	0.229	0.245	28.710	114.839	25.026	100.106
MEAN			1.155	0.359	0.396	0.074	0.046	0.213	0.231	33.196	132.784	28.465	113.860
STDEV			0.111	0.020	0.042	0.010	0.008	0.012	0.015	3.624	14.498	3.415	13.660
1	V_{NE}-5	46	0.836	0.368	0.456	0.069	0.053	0.318	0.330	14.848	59.392	13.802	55.207
1	V_{NE}-5	47	0.861	0.366	0.436	0.067	0.047	0.323	0.333	14.368	57.474	13.495	53.979
1	V_{NE}-5	48	0.788	0.374	0.409	0.066	0.053	0.303	0.315	16.334	65.335	15.162	60.648
1	V_{NE}-5	49	0.822	0.417	0.391	0.067	0.053	0.302	0.314	16.407	65.628	15.201	60.803
1	V_{NE}-5	50	0.785	0.413	0.363	0.067	0.053	0.280	0.293	19.068	76.271	17.465	69.859
1	V_{NE}-5	51	0.800	0.513	0.379	0.074	0.063	0.284	0.300	18.547	74.188	16.627	66.507
1	V_{NE}-5	52	0.868	0.482	0.385	0.090	0.055	0.283	0.302	18.772	75.089	16.474	65.897
1	V_{NE}-5	53	0.858	0.407	0.438	0.069	0.049	0.335	0.346	13.336	53.345	12.537	50.149
1	V_{NE}-5	54	0.822	0.377	0.427	0.065	0.049	0.338	0.348	13.103	52.413	12.387	49.546
1	V_{NE}-5	55	0.886	0.371	0.496	0.069	0.044	0.387	0.396	10.013	40.053	9.586	38.343
MEAN			0.833	0.409	0.418	0.070	0.052	0.315	0.328	15.480	61.919	14.273	57.094
STDEV			0.035	0.051	0.040	0.007	0.005	0.033	0.030	2.915	11.660	2.394	9.577

Table A- 5. UH-1N Statistical Results for Directional Effects (Significant differences at $P<0.05$)

Airspeed	Pilot				Flight Engineer		
	Seat Base	Seat Pan	Seat Back	Helmet	Floor	Seat Pan	Seat Back
80 KIAS	Z>Y>X	X>Z>Y	X>Z>Y	Y>(X=Z)	Z>Y>X	X>Z>Y	Z>X>Y
100 KIAS	(Y=Z)>X	X>Y>Z	Z>X>Y	Y>X>Z	Z>Y>X	X>(Y=Z)	Z>X>Y
V_{NE}-5 KIAS	Z>Y>X	X>(Y=Z)	Z>(X=Y)	Y>X>Z	Z>Y>X	X>(Y=Z)	X>Z>Y

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711th Human Performance Wing
AFRL	Air Force Research Laboratory
APHC	Army Public Health Center
BPF	Blade Passage Frequency
CBDN	Collaborative Biomechanics Data Network
DAU	Data Acquisition Units
FE	Flight Engineer
FLTS	Flight Test Squadron
HGCZ	Health Guidance Caution Zones
Hz	Hertz (cycles per second)
ISO	International Organization for Standardization
KIAS	Knots Indicated Airspeed
LDTO	Lead Development Test Organization
MIL-STD	Military Standard
NDCEE	National Defense Center for Energy and Environment
MOA	Memorandum of Agreement
Nf	Free Turbine Speed
NGB	National Guard Bureau
PRF	Propeller Rotation Frequency
PTO	Participating Test Organization
REVER	Remote Vibration Environment Recorder
RH	Airman Systems Directorate
SRB	Safety Review Board
TRB	Technical Review Board
TW	Test Wing
VMC	Visual Meteorological Conditions
V_{NE}-5	Velocity Not to Exceed – 5
VT ARNG	Vermont Army National Guard
rms	root-mean-square
%	percent
a_{rms}	root-mean-square (rms) 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)