

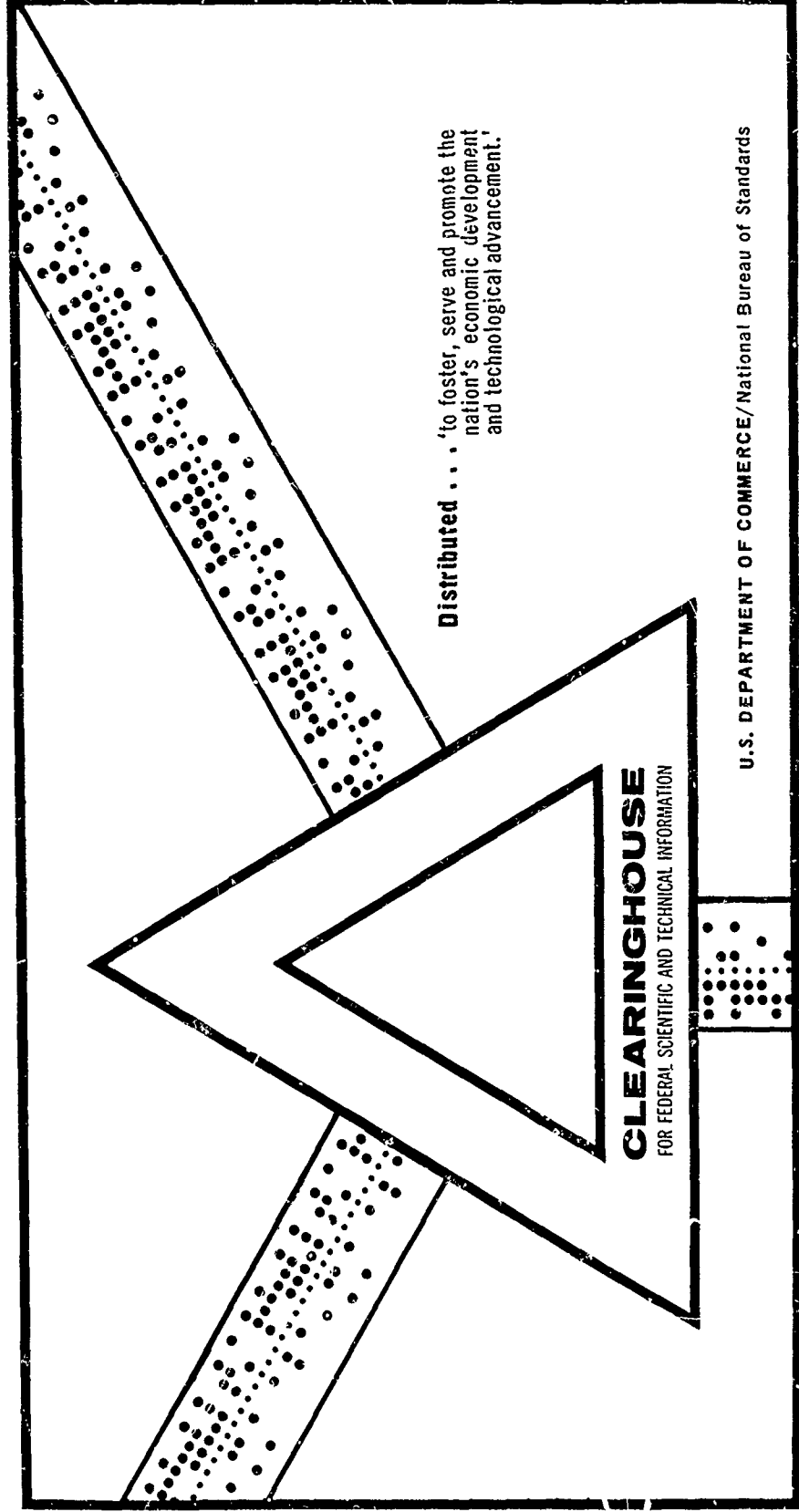
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EFFECTS OF VIBRATION ON NAVY AND MARINE CORPS HELICOPTER  
FLIGHT CREWS

James M. Ketchel, et al

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Alexandria, Virginia

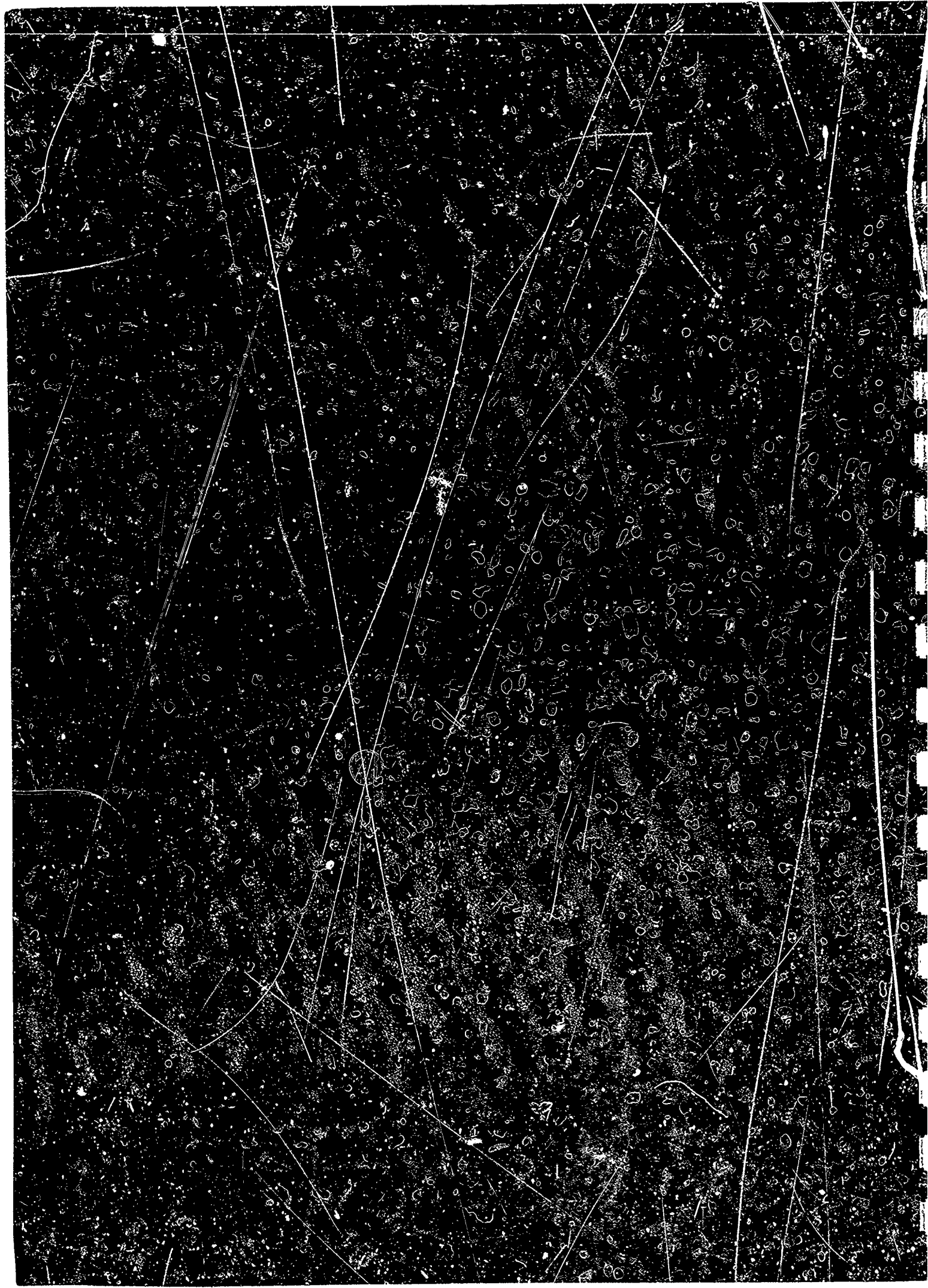
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EFFECTS OF VIBRATION ON NAVY AND MARINE CORPS  
HELICOPTER FLIGHT CREWS

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## ABSTRACT

Identifiable vibration characteristics of contemporary military helicopters are described. These provide a basis for analyzing and interpreting the literature on vibration research. Emphasis is given to experimental results which relate to frequencies and acceleration amplitudes falling within the helicopter main rotor effects region.

The spectrum of military helicopters is tabulated briefly and six representative Navy/Marine Corps helicopters, missions and associated flightcrew tasks are described in more detail.

Perceptual-motor behaviors comprising crew tasks in the six missions are identified. These are used to relate vibration analysis results to the helicopter situation. Qualitative estimates of the susceptibility of present and future mission tasks to the helicopter vibration regime are made.

Helicopter flight equipment items such as seats, helmets, helmet-mounted displays, and various other sophisticated electronic devices are analyzed to assess their relevance to crew vibration performance. Duration of exposure, temperature, ventilation, fatigue, and other factors are discussed as they operate in concert with vibration to degrade helicopter flight crew performance.

Generalizations are drawn from the research literature and conclusions and recommendations are presented in the areas of: physiological effects, performance effects, subjective tolerance data, on-board crew equipment, integrated displays, vibration isolation and absorption techniques, medical and accident record keeping, design specifications and standards, and additional research requirements.

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## SYNTHESIS OF RESULTS

At the outset it should be stated that the most important finding of this study is as follows:

An appallingly small amount of directly applicable experimental data exists on the vibration environment in operational helicopters. Moreover, almost no data have been collected under controlled conditions in an operational setting to determine the effects of this helicopter vibration regime on flight crew performance and physiology.

Therefore, it has been necessary to base conclusions and recommendations on (1) user reactions, and (2) available laboratory studies, which often only approximate the vibration conditions, and which frequently involve the performance of tasks only generally resembling those of helicopter crewmen. Nevertheless, based on the available evidence it is concluded that prolonged exposure to the helicopter operational environment produces adverse effects on flight crews. These effects are detailed in the following pages as conclusions. The evidence, and the lack of it point up an urgent need for additional research as a basis for identifying the true magnitude of the problems and for prescribing more specific remedial measures.

This portion of the report is presented in three parts:

- (1) Conclusions and problem areas based upon available data, as well as recommended solutions and courses of action.
- (2) Reported problem areas and relevant laboratory research results summarized in tabular form.
- (3) Problems requiring further study.

## 1. CONCLUSIONS AND RECOMMENDATIONS

### General Effects of Vibration

Conclusion 1: Responses from a number of independent military facilities, as well as laboratory research literature indicate that helicopter vibration is a chronic problem. Moreover, vibration undoubtedly acts in concert with noise, temperature and other environmental variables to cause fatigue, degrade performance, and adversely affect physiological status. p. 11.

Recommendation 1: Research is needed on the interactive effects of multiple stressors.

Conclusion 2: Military helicopter missions often last for periods of 4 to 8 hours with little or no rest between sorties. p. 73, 147, 152.

Recommendation 2: Until more definitive data become available concerning the effects of prolonged exposure to helicopter vibration, it is recommended that the maximum duration of exposure for a flight crewman should not exceed four hours during any 24-hour period.

Conclusion 3: Under helicopter vibration conditions, a high probability of error is expected in the operation of cockpit controls (pushbuttons, toggles, rotary switches and thumbwheels). p. 20, 21, 107.

Recommendation 3: Consideration should be given to increasing the spring forces and breakout forces of controls to reduce the likelihood of operating errors such as inadvertent actuation and selection of inappropriate settings on the controls.

Conclusion 4: Visual acuity is impaired by the helicopter vibration regime. Flight crew performance in dial and number reading tasks can be expected to suffer under such conditions. p. 15, 16.

Recommendation 4: Helicopter display characters and symbology sizes should be increased wherever possible; and other measures for improving display legibility in the helicopter vibration environment should be explored.

Conclusion 5: Research evidence indicates that, in spite of the attenuation characteristics of the body, vibration of the subject (operator) is more detrimental to visual acuity than vibration of the viewed object. p. 15.

Recommendation 5: Attenuation efforts should focus on isolation of the subject as a primary goal, with isolation of the viewed

object as an important but subordinate consideration.

Conclusion 6: Fleet maintenance practices with regard to rotor blade tracking tolerance and blade charging may constitute an effective means for controlling helicopter vibration during the course of aircraft in-service aging. p.51, 123.

Recommendation 6: Determine the extent to which current fleet maintenance practices and procedures limit helicopter vibration over aircraft service life. Specifically, determine whether the acceleration curves recorded from new aircraft match those for similar aircraft after a period of exposure to fleet conditions, and how much disparity exists at various points in the maintenance cycle across a representative sample of maintenance facilities.

Conclusion 7: In many cases combinations of helicopter dominant rotor frequencies and acceleration amplitudes are clearly beyond the limits specified by MIL-H-8501A and Technical Committee 108 standards. p. 152.

Recommendation 7: Techniques for reducing the adverse effects of vibration must be evaluated. Representative techniques include vibration isolation, restraint design, and use of helmet mounted devices.

Conclusion 8: In many instances the applicability and validity of MIL-H-8501A standards can be questioned due to the inadequacy of experimental data and the omission of exposure duration limits. p.148.

Recommendation 8: MIL-H-8501A must be updated as adequate research findings become available. It must also include specification of exposure duration limits.

Conclusion 9: Significant crew performance decrements can be expected on compensatory tracking tasks involving synthetic displays in the helicopter vibration environment. p.17-20, 105.

Recommendation 9: Prolonged IFR flying (2 hours or more) by helicopter pilots should be avoided whenever practicable. On-board relief pilots are not an adequate solution since they are exposed to the helicopter environment even when not on duty.

#### Effects of Vibration on Mission Specific Operations

Conclusion 1: Analysis of six representative Navy/Marine Corps helicopter missions indicates that nearly all pilot/copilot flight tasks are likely to be adversely affected by vibration exposure for nominal mission durations. p.102-119, 120.

Recommendation 1: Research must be performed on vibration effects in terms of mission tasks.

Conclusion 2: In general, the nature of most non-pilot crew tasks is such that they are less susceptible to degraded performance under the helicopter vibration regime than pilot tasks. p.106, 110, 111, 114.

Recommendation 2: Priority should be given to reducing the adverse effects of vibration on pilots.

Conclusion 3: Sonar operator tasks in the ASW mission and the aerial gunner/observer tasks in both the Assault Support and Advanced Aerial Fire Support missions are highly susceptible to effects of vibration. p.106, 114.

Recommendation 3: For non-pilot operations, priority should be given to reduction of effects of vibration on these activities.

Conclusion 4: Of the six present day helicopter missions and associated crew tasks analyzed, the Anti-Submarine Warfare (ASW) mission ranks as the most demanding and the most susceptible to vibration effects. However, the Search and Rescue (SAR) and the Assault Support (Fire Control) missions also fall into the category of being highly susceptible. p.106, 114, 121.

Recommendation 4: These missions should receive emphasis in the development of techniques to reduce effects of vibration.

Conclusion 5: Tasks requiring displays to present sensed information such as radar, IR, and LLLTV, wherein complex pattern recognition is involved, will be adversely affected by vibration. To a lesser extent, crew performance in the use of pictorial displays having stylized symbology is also likely to be degraded under helicopter vibration conditions. p. 115-120.

Recommendation 5: The effectiveness of helmet mounted display devices to present information in helicopters should be investigated.

#### Seats and Other Equipment

Conclusion 1: Seat design is inadequate in most contemporary helicopters. Complaints by crewmen regarding helicopter seat design are widespread. The most frequently voiced shortcomings seem to be: lack of adjustment, circulation interference, inadequate cushioning, poor ventilation, lack of a headrest and lack of support in the lower lumbar region. p. 11, 137-141.

Recommendation 1: The effectiveness of proposed seat design concepts must be established. An improved helicopter seat design should be made available for installation in operational helicopters. Such a seat should include the following characteristics: capable of adjustment in the up/down, fore/aft, and pivot or tilt angle directions; improved cushioning, particularly at the forward edge of the seat pan; improved support in the lower lumbar region; improved ventilation, addition of headrest.

Conclusion 2: In many cases flight crew restraint and support systems do not provide adequate protection, particularly in the lateral direction. Moreover, shoulder and chest support is considered inadequate in those helicopters which characteristically cruise in a pitch-down attitude. p.11, 137, 138, 140.

Recommendation 2: An improved restraint and support system, providing better chest and shoulder support and lateral restraint, should be made available for installation in currently operational fleet helicopters, and should be incorporated into future helicopter designs.

Conclusion 3: The collective pitch control in some military helicopters requires a forward leaning movement and bending of the spine at a point in time where vibration is relatively intense. p. 94, 99, 138.

Recommendation 3: Consider redesign of the collective pitch control so that the full low stop can be reached without excessive bending of the spine.

Conclusion 4: In-flight tracking systems for rotor blades constitute an effective and efficient means for the pilot to bring his rotor blades into track under a variety of flight conditions, and hence, to attenuate a source of low frequency vibration. Such systems are presently available and are particularly well suited for 2- and 4-blade helicopter applications. p. 123.

Recommendation 4: The feasibility of incorporating in-flight blade tracking devices into helicopter designs should be investigated.

#### Other Physical Factors

Conclusion 1: The occurrence and extent of performance impairment in flight crew personnel as a result of fatigue has not been adequately documented. p. 11, 145-147.

Recommendation 1: Continued efforts should be made to identify the conditions which cause fatigue in helicopter crewmen, to describe its characteristics and symptoms, and to establish its effects on performance.

Conclusion 2: High ambient noise levels are prevalent in most currently used Navy/Marine Corps helicopters. This noise may jeopardize the health and efficiency of exposed crewmembers by causing permanent or temporary hearing losses, and general discomfort or fatigue. p. 11, 133-136.

Recommendation 2: Greater emphasis should be placed on overall acoustical design improvements in helicopters in order to minimize the impact of noise on aircrew performance and bio-medical status.

Conclusion 3: Test results indicate that both the SPH-3 helmet and Gentex earcups constitute effective noise attenuation equipment. Anecdotal evidence also indicates that they are widely recognized for their comfort and effectiveness. p. 11, 135.

Recommendation 3: Action should be taken to expedite the widespread distribution of these and comparable noise attenuation equipments to operational helicopter flight personnel.

Conclusion 4: Excessive cabin temperatures constitute a significant source of discomfort to helicopter crewmen. Contemporary helicopters use ram-air ventilation, thereby achieving some relief during forward cruise. However, during ground operations and while engaged in extended hover, cockpit and cabin heat is often excessive. p. 11, 142, 157.

Recommendation 4: The feasibility of retrofitting certain currently operating helicopters with air conditioning (or at least improved ventilation systems) should be investigated. Serious consideration should be given to the incorporation of air conditioning into new helicopter designs.

Conclusion 5: Flight crew susceptibility to disorientation and vertigo is likely to be increased under the combined influence of vibration and marginal weather or night flights. The threat posed by these factors can probably be minimized by the use of electronic displays, provided that cockpit lighting is of appropriate uniformity and intensity. p. 11, 158-159.

Recommendation 5: Steps should be taken to investigate problems of disorientation and methods of solution.

Conclusion 6: Complaints have been voiced by pilots and crewmen regarding the adverse effects of flashing and flickering lights, or rotating beacons. Such phenomena evidently are irritating to substantial numbers of crewmen. p. 11, 120.

Recommendation 6: The severity of the problem of photic stimulation must be established and solutions must be defined.

## 2. REPORTED PROBLEM AREAS AND LABORATORY RESEARCH RESULTS

A summary of reported problem areas specified by seven independent military facilities is presented on the following page. It also appears as Table 1 in Section 1 of this report.

Relevant laboratory research results are also summarized in tabular form on following pages. These results are grouped according to Physiological Effects, Performance Effects, and Subjective Tolerance Data. These data also appear as Tables 4, 5, and 6 in Section 2 of the report.





<p>NOISE</p> <ul style="list-style-type: none"> <li>High noise levels interfere with communications and comfort. This could be alleviated by use of Gentex Sonic Ear Cups or the SPH-3B Sound Protective Helmet.</li> <li>Noise was the most often mentioned source of fatigue and discomfort. ... this factor is intensified by the shortage of SPH-3 helmets and sonic ear cups.</li> <li>A long standing fatigue factor affecting helicopter flight crew members is the high noise level ... This factor will be largely eliminated when the Gentex Sonex ear cushions become available to all aircrewmembers.</li> <li>Noise hazard, especially in the low frequency ranges (105 to 115 db in the 70 to 100 Hz bands), ... presents a definite problem.</li> </ul>						4
<p>HEAT/VENTILATION</p> <ul style="list-style-type: none"> <li>ASW hover. excessive cabin heat</li> <li>Center console heat more intense at bottom edge. Additional and better located heat ports needed.</li> <li>Another discomfort factor is heat, especially on long hover situations. Improved blowers would help.</li> <li>The large bubble type cockpit exposes the pilot directly to the heat of the sun.</li> </ul>						4
<p>FUMES</p> <ul style="list-style-type: none"> <li>Carbon monoxide fumes can be dangerous in the H-34 helicopter in an "out-of-the-wind" hover, and this maneuver is forbidden. ... It is difficult to determine wind direction with ... accuracy in mountain rescue flights.</li> </ul>						1
<p>SEATS</p> <ul style="list-style-type: none"> <li>A great deal of discomfort seems to be caused by the present seat design. A definite need for a fore-aft, up-down seat as found in the UH-1 is indicated ... Seat security, is questioned ... Lack of padding behind the calf ... causes a loss of sensation. Seat Buttocks fatigue after 2.5 to 3 hrs. ... is very annoying. Seat stimulating cushions should be investigated.</li> <li>The most prevalent complaint was the extreme discomfort of seats, especially in the UH-1E &amp; B and CH-46D &amp; F aircraft. Lack of adequate seat adjustments, ... comfortable cushions, and shoulder support causes considerable discomfort ... This discomfort becomes apparent after about 45 minutes.</li> <li>The observations of those consulted on this subject seem to focus on the helicopter seats. On a typical 4 or 5-hour mission, every member of the crew complains of some degree of lumbar pain. Another complaint is the lack of a headrest.</li> </ul>						4
<p>VISION</p> <ul style="list-style-type: none"> <li>No accurate detection of drift and rotation - caused by lack of instrument and visual cues.</li> <li>Present cockpit design requires too great a period of time for a proper scan pattern of the instruments. Primary instruments are widely separated, ... some ... are not duplicated for the copilot. Attempts to scan a constantly vibrating instrument panel during IFR ... induces long lasting eye fatigue. Additional eye fatigue and disorientation occur as a result of "the strobe effect" of a rotating beacon on the belly ... reflecting off the water at night. Lights ... at the console ... reflect off the windshield resulting in blind spots and a reduction in depth perception. No horizon black nights with 3 to 4 light durations at or below 150 ft. is anxiety factor that induces fatigue in the most competent pilot.</li> <li>... the "flicker illumination effect" resulting from ... filtration of sunlight through rotor blades or the reflection of aircraft lights on them (at) night ... has the potential for "hypnotizing" and most certainly produces some visual discomfort and subsequent fatigue. Rotor downwash ... produces considerable water spray during low hover ... above water. When this spray is deflected</li> </ul>						3

<ul style="list-style-type: none"> <li>• No accurate detection of drift and rotation - caused by lack of instrument and visual cues.</li> <li>• Present cockpit design requires too great a period of time for a proper scan pattern of the instruments. Primary instruments are widely separated, ... some ... are not duplicated for the copilot. Attempts to scan a constantly vibrating instrument panel during IFR ... induces long lasting eye fatigue. Additional eye fatigue and disorientation occur as a result of "the strobe effect" of a rotating beacon on the belly ... reflecting off the water at night. Lights ... at the console ... reflect off the windshield resulting in blind spots and a reduction in depth perception. No horizon black nights with 3 to 4 flight durations at or below 150 ft. is anxiety factor that induces fatigue in the most competent pilot.</li> <li>• ... the "flicker illumination effect" resulting from ... filtration of sunlight through rotor blades or the reflection of aircraft lights on them (at) night ... has the potential for "hypnotizing" and most certainly produces some visual discomfort and subsequent fatigue. Rotor downwash ... produces considerable water spray during low hover ... above water. When this spray is deflected over the cockpit windows at night, outside visibility is significantly reduced. ... supplemental oxygen system will be essential ... at altitudes above 5,000 ft., if hypoxic effects on night visual acuity are to be avoided.</li> </ul>	•	•	•	•	•	•	3
<p>DISORIENTATION AND INSTRUMENTS</p> <ul style="list-style-type: none"> <li>• The instrument read-out in helicopter flight is different than that of fixed-wing aircraft ... An example is in the interpretation of the horizontal gyroscope that indicates descent when the helicopter is nose-down in a climb.</li> <li>• Spatial disorientation - under conditions of reduced visibility especially during hover and departing. No accurate detection of drift and rotation caused by lack of instrument and visual cues.</li> <li>• ... eye fatigue and disorientation caused by "strobe effect" of rotating beacon.</li> <li>• All agreed that spatial disorientation and flicker vertigo are always possible in IFR and marginal VFR conditions ...</li> <li>• ... flying through clouds in large bubble helicopters, a pilot may easily experience disorientation or vertigo caused by the rapid movement of clouds past all sides of the cockpit ... night operations magnify this disorientation potential through the reflection of helicopter lights on the clouds. Lack of suitable position reference ... major problem in night recovery.</li> </ul>	•	•	•	•	•	•	5
<p>DURATION OF MISSION</p> <ul style="list-style-type: none"> <li>• The greatest occupational factor inducing fatigue is the increase in the mission capabilities of the helicopter, for example, the ASW missions of the H-3. These flights, averaging 4 to 6 hours, are definitely overly demanding of the man/machine complex as demonstrated by the increased occurrence of incidents with longer flight durations.</li> <li>• Lack of effective communications between pilots and supervisors aboard CVS carriers ... it was very difficult to convince officers of the complexities and short-comings of helicopters ... to perform various rescue missions ... Lack of comfortable sitting room for aircrewmembers in back of several small Navy helicopters.</li> <li>• Aircrew feeding and waste elimination facilities available on either HH 3 E or HH 53 B/C series helicopters are totally inadequate. The addition of improved navigational equipment, automatic flight control systems, and ultimately, sub-systems for automatically controlled approach and hover, terrain avoidance during low level "blind flight" ... will greatly increase the scope of operational capabilities for future helicopters and will ... add additional stresses on helicopter aircrew members.</li> </ul>	•	•	•	•	•	•	3

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TABLE 2 PHYSIOLOGICAL EFFECTS

MAIN ROTOR EFFECTS (DOM FREQ)	HELICOPTER VIBRATION FREQUENCY RANGE (Hz)	ACCELERATION g's OR DISPLACEMENT AMPLITUDES & EXPOSURE DURATION	REMARKS
	2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 40 50 60 70 80 90 100		<p>Whole Body Resonance</p> <p>Whole Body Resonance Head Resonance (20-35 Hz)</p> <p>Eyeball Resonance</p> <p>Thorax-Abdomen Major Resonance</p> <p>General Discomfort Load Sensations Jaw Symptoms (Resonance) Speech Affected Pharynx Tug or Lump in Throat Chest Pains Respiration Respiration Voluntary Muscular Constriction Abdominal Pain Lumbosacral Pain Dizziness Involuntary Muscle Tone</p> <p>Axial Compression of the spine</p> <p>Head Resonance</p> <p>Soft Tissue of Neck &amp; Scalp</p> <p>First Resonance of Eyeball May Occur Here</p> <p>Tissue Over Chestbone</p>

TABLE 3 PERFORMANCE EFFECTS

MAIN ROTOR EFFECTS (DOM FREQ)															FREQUENCY RANGE / Hz										ACCELERATION G'S OR DISPLACEMENT AMPLITUDES & EXPOSURE DURATION	S & S	TASKS & RESULTS																
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	40	50	60	70	80	90	100																						
1-5 Hz HORNIK 1961																								VISUAL ACUITY AND OTHER TASKS Both vertical and lateral axis vibration studied																			
																						Z	0.15, 0.25, 0.35g																			30	1. Visual Acuity - Decrement found following exposure
																						Y	0.15, 0.25, 0.35g (exposure duration not specified in abstract)																			20	2. Maintenance of constant foot pressure affected most at 1.5 and 2.5 Hz
																																											3. Tracking performance affected by Y axis vibration most decrementally at 1.5 Hz
																																											4. Reaction times slower following exposure to vertical vibration
																																											5. Tracking performance affected decrements also significant for vertical vib.
																																											6. 1.5 and 2.5 Hz impaired peripheral vision initially, but peripheral vision following transverse vibration was improved
																						Z	0.069, 0.034, 0.030 inches DA (light vib.)																			6	1. Visual Acuity, Manual Tremor, and Aiming Tremor measured. All showed greatest impairment at 15 Hz
																							0.112, 0.056, 0.050 inches DA (hvy vib.)																			5	2. Noise not significant
																							115 db noise (3rd condit) (2.5 hrs. exposure per session)																			6	3. Trial and condition interactions significant; not frequency
																						Z	Constant 0.6g or 0.25 cm dbl amplitudes used (15 min. exposure)																			4	1. Visual Acuity - contrast ratio varied - S alone vibrated; then S and display both vibrated (in-phase assumed) - bite bar - no bite bar conditions
																																											2. Found - similar to Taub (1964) A constant acceleration of ± 0.6g produced decrement in performance inversely related to frequency between 6 and 15 Hz. Within each frequency (without bite bar) quality of performance varied inversely with amplitude
																							LOEB 1954																				
																							RUBINSTEIN (dici) & TAUB 1967																				

TABLE 3 (cont)

MAIN ROTOR EFFECTS (DOM FREQ)									
HELICOPTER VIBRATION FREQUENCY RANGE (Hz)									
2	4	6	8	10	12	14	16	18	20
22	24	26	28	30	32	34	36	38	40
42	44	46	48	50	52	54	56	58	60
62	64	66	68	70	72	74	76	78	80
82	84	86	88	90	92	94	96	98	100
POOREST ACUITY									
RUBENSTEIN & KAPLAN 1968									
OSHIKAWA 1962 (cited in RUBENSTEIN & KAPLAN 1968)									
COORMAN 1968 (cited in RUBENSTEIN & KAPLAN 1968)									
TASKS & RESULTS									
S's									
ACCELERATION g's OR DISPLACEMENT AMPLITUDES & EXPOSURE DURATION									
Y									
Z									
X Y Z									
1. Visual Acuity - Contrast ratio varied - 4 experiments; tail vibration, 10 Hz target vibration, 10 Hz head vibration with target oriented horizontally of 1.0g - acuity poorest between 22 to 34 Hz (low point at 26 Hz); beyond 34 Hz acuity improves with increased frequency									
2. In exp. III decrements in acuity caused by target vibration less than for head vibration (Oshikawa's data confirmed)									
3. Pooled data show acuity decrements at 13, 26, 34, 52, and 58 Hz for constant displacement amplitude, .03 cm; acuity is at a maximum at 13 Hz. It dips steadily to a low at 30 Hz; then improves with increasing frequency to 70 Hz									
4. Visual Acuity - comparison of only target vibrating to only subject vibrating									
5. Sound - between 2 and 10 Hz. Performance was closely related to relative displacement of eye and target. Beyond 10 Hz, only vibration of subject produced additional acuity decrements.									
6. Body attenuation not withstanding, the evidence suggests vibration of subject more detrimental to performance than vib. of tgt.									
7. Visual Acuity - Greatest decrements reported in these frequency bands									
DIAL AND NUMBER READING									
8. Easy dial reading task not affected									
9. Difficult task errors visible directly with acceleration level									
10. Speed not affected									

TABLE 3 (cont.)

[illegible]

TABLE 3 (cont)

MAIN ROTOR EFFECTS (DOM FREQ)											
HELICOPTER VIBRATION FREQUENCY RANGE (Hz)											
2	4	6	8	10	12	14	16	18	20	22	24
24	26	28	30	32	34	36	38	40	42	44	46
48	50	52	54	56	58	60	62	64	66	68	70
72	74	76	78	80	82	84	86	88	90	92	94
96	98	100	102	104	106	108	110	112	114	116	118
120	122	124	126	128	130	132	134	136	138	140	142
144	146	148	150	152	154	156	158	160	162	164	166
168	170	172	174	176	178	180	182	184	186	188	190
192	194	196	198	200	202	204	206	208	210	212	214
216	218	220	222	224	226	228	230	232	234	236	238
240	242	244	246	248	250	252	254	256	258	260	262
264	266	268	270	272	274	276	278	280	282	284	286
288	290	292	294	296	298	300	302	304	306	308	310
312	314	316	318	320	322	324	326	328	330	332	334
336	338	340	342	344	346	348	350	352	354	356	358
360	362	364	366	368	370	372	374	376	378	380	382
384	386	388	390	392	394	396	398	400	402	404	406
408	410	412	414	416	418	420	422	424	426	428	430
432	434	436	438	440	442	444	446	448	450	452	454
456	458	460	462	464	466	468	470	472	474	476	478
480	482	484	486	488	490	492	494	496	498	500	502
504	506	508	510	512	514	516	518	520	522	524	526
528	530	532	534	536	538	540	542	544	546	548	550
552	554	556	558	560	562	564	566	568	570	572	574
576	578	580	582	584	586	588	590	592	594	596	598
600	602	604	606	608	610	612	614	616	618	620	622
624	626	628	630	632	634	636	638	640	642	644	646
648	650	652	654	656	658	660	662	664	666	668	670
672	674	676	678	680	682	684	686	688	690	692	694
696	698	700	702	704	706	708	710	712	714	716	718
720	722	724	726	728	730	732	734	736	738	740	742
744	746	748	750	752	754	756	758	760	762	764	766
768	770	772	774	776	778	780	782	784	786	788	790
792	794	796	798	800	802	804	806	808	810	812	814
816	818	820	822	824	826	828	830	832	834	836	838
840	842	844	846	848	850	852	854	856	858	860	862
864	866	868	870	872	874	876	878	880	882	884	886
888	890	892	894	896	898	900	902	904	906	908	910
912	914	916	918	920	922	924	926	928	930	932	934
936	938	940	942	944	946	948	950	952	954	956	958
960	962	964	966	968	970	972	974	976	978	980	982
984	986	988	990	992	994	996	998	1000	1002	1004	1006
1008	1010	1012	1014	1016	1018	1020	1022	1024	1026	1028	1030
1032	1034	1036	1038	1040	1042	1044	1046	1048	1050	1052	1054
1056	1058	1060	1062	1064	1066	1068	1070	1072	1074	1076	1078
1080	1082	1084	1086	1088	1090	1092	1094	1096	1098	1100	1102
1104	1106	1108	1110	1112	1114	1116	1118	1120	1122	1124	1126
1128	1130	1132	1134	1136	1138	1140	1142	1144	1146	1148	1150
1152	1154	1156	1158	1160	1162	1164	1166	1168	1170	1172	1174
1176	1178	1180	1182	1184	1186	1188	1190	1192	1194	1196	1198
1200	1202	1204	1206	1208	1210	1212	1214	1216	1218	1220	1222
1224	1226	1228	1230	1232	1234	1236	1238	1240	1242	1244	1246
1248	1250	1252	1254	1256	1258	1260	1262	1264	1266	1268	1270
1272	1274	1276	1278	1280	1282	1284	1286	1288	1290	1292	1294
1296	1298	1300	1302	1304	1306	1308	1310	1312	1314	1316	1318
1320	1322	1324	1326	1328	1330	1332	1334	1336	1338	1340	1342
1344	1346	1348	1350	1352	1354	1356	1358	1360	1362	1364	1366
1368	1370	1372	1374	1376	1378	1380	1382	1384	1386	1388	1390
1392	1394	1396	1398	1400	1402	1404	1406	1408	1410	1412	1414
1416	1418	1420	1422	1424	1426	1428	1430	1432	1434	1436	1438
1440	1442	1444	1446	1448	1450	1452	1454	1456	1458	1460	1462
1464	1466	1468	1470	1472	1474	1476	1478	1480	1482	1484	1486
1488	1490	1492	1494	1496	1498	1500	1502	1504	1506	1508	1510
1512	1514	1516	1518	1520	1522	1524	1526	1528	1530	1532	1534
1536	1538	1540	1542	1544	1546	1548	1550	1552	1554	1556	1558
1560	1562	1564	1566	1568	1570	1572	1574	1576	1578	1580	1582
1584	1586	1588	1590	1592	1594	1596	1598	1600	1602	1604	1606
1608	1610	1612	1614	1616	1618	1620	1622	1624	1626	1628	1630
1632	1634	1636	1638	1640	1642	1644	1646	1648	1650	1652	1654
1656	1658	1660	1662	1664	1666	1668	1670	1672	1674	1676	1678
1680	1682	1684	1686	1688	1690	1692	1694	1696	1698	1700	1702
1704	1706	1708	1710	1712	1714	1716	1718	1720	1722	1724	1726
1728	1730	1732	1734	1736	1738	1740	1742	1744	1746	1748	1750
1752	1754	1756	1758	1760	1762	1764	1766	1768	1770	1772	1774
1776	1778	1780	1782	1784	1786	1788	1790	1792	1794	1796	1798
1800	1802	1804	1806	1808	1810	1812	1814	1816	1818	1820	1822
1824	1826	1828	1830	1832	1834	1836	1838	1840	1842	1844	1846
1848	1850	1852	1854	1856	1858	1860	1862	1864	1866	1868	1870
1872	1874	1876	1878	1880	1882	1884	1886	1888	1890	1892	1894
1896	1898	1900	1902	1904	1906	1908	1910	1912	1914	1916	1918
1920	1922	1924	1926	1928	1930	1932	1934	1936	1938	1940	1942
1944	1946	1948	1950	1952	1954	1956	1958	1960	1962	1964	1966
1968	1970	1972	1974	1976	1978	1980	1982	1984	1986	1988	1990
1992	1994	1996	1998	2000	2002	2004	2006	2008	2010	2012	2014
2016	2018	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038
2040	2042	2044	2046	2048	2050	2052	2054	2056	2058	2060	2062
2064	2066	2068	2070	2072	2074	2076	2078	2080	2082	2084	2086
2088	2090	2092	2094	2096	2098	2100	2102	2104	2106	2108	2110
2112	2114	2116	2118	2120	2122	2124	2126	2128	2130	2132	2134
2136	2138	2140	2142	2144	2146	2148	2150	2152	2154	2156	2158
2160	2162	2164	2166	2168	2170	2172	2174	2176	2178	2180	2182
2184	2186	2188	2190	2192	2194	2196	2198	2200	2202	2204	2206
2208	2210	2212	2214	2216	2218	2220	2222	2224	2226	2228	2230
2232	2234	2236	2238	2240	2242	2244	2246	2248	2250	2252	2254
2256	2258	2260	2262	2264	2266	2268	2270	2272	2274	2276	2278
2280	2282	2284	2286	2288	2290	2292	2294	2296	2298	2300	2302
2304	2306	2308	2310	2312	2314	2316	2318	2320	2322	2324	2326
2328	2330	2332	2334	2336	2338	2340	2342	2344	2346	2348	2350
2352	2354	2356	2358	2360	2362	2364	2366	2368	2370	2372	2374
2376	2378	2380	2382	2384	2386	2388	2390	2392	2394	2396	2398
2400	2402	2404	2406	2408	2410	2412	2414	2416	2418	2420	2422
2424	2426	2428	2430	2432	2434	2436	2438	2440	2442	2444	2446
2448	2450	2452	2454	2456	2458	2460	2462	2464	2466	2468	2470
2472	2474	2476	2478	2480	2482	2484	2486	2488	2490	2492	2494
2496	2498	2500	2502	2504	2506	2508	2510	2512	2514	2516	2518
2520	2522	2524	2526	2528	2530	2532	2534	2536	2538	2540	2542
2544	2546	2548	2550	2552	2554	2556	2558	2560	2562	2564	2566
2568	2570	2572	2574	2576	2578	2580	2582	2584	2586	2588	2590
2592	2594	2596	2598	2600	2602	2604	2606	2608	2610	2612	2614
2616	2618	2620	2622	2624	2626	2628	2630	2632	2634	2636	2638
2640	2642	2644	2646	2648	2650	2652	2654	2656			



TABLE 3 (cont.)

MAIN ROTOR EFFECTS (DOM FREQ)																	
HELICOPTER VIBRATION FREQUENCY RANGE (Hz)																	
2	4	6	8	10	12	14	16	18	20								
22	24	26	28	30	40	50	60	70	80								
90	100	H. S.															
ACCELERATION g's OR DISPLACEMENT AMPLITUDES & EXPOSURE DURATION																	
TASKS & RESULTS																	
RANDOM VIBRATION																	
1. Fly from tracking on CRT display, primary task																	
2. Visual reaction task - monitor and respond to 3 red and 3 green lights																	
3. Auditory task - respond to auditory signal																	
Found -																	
1. Horizontal tracking error smaller, even during static conditions																	
2. Warning light performance not significantly affected																	
3. Serious tracking performance decrements not found up to 0.16g RMS																	
4. Performance improvements during 2nd and 6th hours indicate danger of extrapolating long-term performance data from relatively short exposure																	
24																	
1. Compensatory tracking on CRT display																	
2. Visual reaction task maintain 3 green lights on and 3 red lights off																	
3. Auditory vigilance task monitor tones and respond to change in pitch																	
Found - First experiment																	
1. Performance differed significantly with increasing acceleration levels																	
2. Task difficulty significant for vertical tracking only																	
3. Subject variability noted																	
4. Significant decrements in both horizontal and vertical tracking appeared at lowest level of sinusoidal vib. tested, 5 Hz (0.035 RMSg) for random vibration, decrements 1st appeared at higher levels, (0.106 and 0.177 RMSg)																	

H. S.									
Every Peaks at 2 & 5 Hz									
HOLLAND, 1965.									
Random									
Random									
Sinusoidal									
WIESE, GODDARD, & ALDEN 1965									

TABLE 3 (cont)

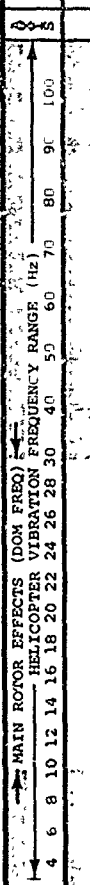
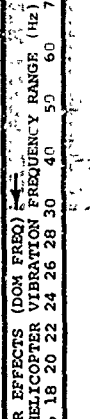
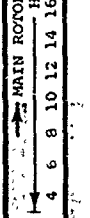
MAIN ROTOR EFFECTS (DOM FREQ) 											
HELICOPTER VIBRATION FREQUENCY RANGE (Hz)											
2	4	6	8	10	12	14	16	18	20	22	24
26	28	30	40	50	60	70	80	90	100	ACCELERATION g's OR DISPLACEMENT AMPLITUDES & EXPOSURE DURATION	
											g's
											
											
HORNICK & LEPRITZ 1966											
Predominant Energy @ 1 Hz with Peaks @ 7 & 10 Hz											
2											
0.10, 0.15, 0.20 RMSg											
5 hour sessions with center 4 hours under dynamic conditions											
10											
Second experiment											
1. Results similar to exp. 1 plus significant decrements in tracking performance as a function of task complexity											
2. 0.035 RMSg frequently found to be pleasant or relaxing to subjects											
TRACKING - RANDOM VIBRATION											
1. Prolonged random vibration studied, similar to low altitude high speed flight (LHS) profile of fixed wing aircraft terrain following											
2. Primary task: terrain following on CRT display - 250 ft. altitude flown over flat, rolling, or mountainous terrain											
3. Reaction time tested on simulated ECM task (extinguish red light)											
4. Vigilance tested by command/actual thrust display indicator alignment. Scan pattern required											
Found											
1. Flight path error directly related to terrain type											
- post-vs pre- vibration tracking error significant											
- 0.10 to 0.20 RMSg increase did not elicit performance decrements											
- no tracking error increases as function of vib. for flat or rolling terrain											
- for mountainous terrain there is a trend for significant tracking error increases for all vibration intensity levels, this occurs after about 2.5 hrs. of vibration											
2. Sample reaction time not impaired under test conditions											
3. Vigilance - not impaired as a function of vibration intensity level. It is impaired as a function of vibration itself; but does not increase as a function of duration											
4. Tolerance - all S's predicted that they could withstand another 2 hrs. at any intensity level without detriment											
TASKS & RESULTS											

TABLE 3 (cont.)

MAIN ROTOR EFFECTS (DOM FREQ)														ACCELERATION g's OR DISPLACEMENT AMPLITUDES & EXPOSURE DURATION				TASKS & RESULTS					
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	40	50	60	70	80	90	100	12	10
DEAN, PARKER, & HITE 1969																							
1. Operation of decimal input devices studied - 6 input panels used, involving 4 basic controls: pushbuttons, toggles, rotary switches, and thumbwheels - three students - dependent measures: speed, accuracy, preference, and estimated speed and accuracy																							
2. Found - the overall effect of vibration was to degrade performance. No single device was best for speed, accuracy and preference																							
3. 0.8 RMSg caused intense discomfort and pain in the abdomen and thorax of 2 subjects																							

TABLE 4 SUBJECTIVE TOLERANCE DATA

MAIN ROTOR EFFECTS (DOM FREQ)																	
HELICOPTER VIBRATION FREQUENCY RANGE (Hz)																	
2	4	6	8	10	12	14	16	18	20								
22	24	26	28	30	40	50	60	70	80								
90	100																
RESULTS & CONCLUSIONS																	
<p>GORRILL &amp; SNYDER 1957</p> <p>8-15 Hz Lowest Tolerance Range</p> <p>MAUD, GOERNANN, &amp; ZIEGENRUECKER 1960</p> <p>15-15 Hz Lowest Tolerance Range</p> <p>15-15 Hz Low Tolerance Range</p> <p>15-20 Hz High Tolerance Range</p> <p>PARKS &amp; SNYDER 1961</p> <p>15-15 Hz Lowest Tolerance Range</p> <p>15-15 Hz Low Tolerance Range</p> <p>15-15 Hz High Tolerance Range</p> <p>TEARE &amp; PARKS 1963</p> <p>15-15 Hz Lowest Tolerance Range</p> <p>15-15 Hz Low Tolerance Range</p> <p>15-15 Hz High Tolerance Range</p>																	
<p>1. Tracking task decrements significant at 15 Hz and at 1.5g</p> <p>2. Sinusoidal vibrations of 0.5g in the 3 to 30 Hz range should be avoided. At 15 Hz, less than 0.5g is probably required</p> <p>3. At higher frequencies (15-30 Hz) 2.0 to 2.5g can be tolerated by some individuals for short period emergencies</p> <p>4. Note subjects asked to project short exposure responses over time, 0.5g, could a 2 minute exposure level be endured for one hour?</p> <p>1. In the 4-8 Hz range, up to 2.0 g's could be tolerated</p> <p>2. Subject tolerance variability noted</p> <p>1. Curves plotted for 4 levels of subjective judgement between 1 to 27 Hz</p> <p>Level 1 Definitely perceptible</p> <p>Level 2 Mildly annoying</p> <p>Level 3 Extremely annoying</p> <p>Level 4 Alarming</p> <p>For all curves tolerance is generally highest between 4-8 Hz and below 2 Hz acceleration level ranges from approximately 0.1g at 1 and 5 Hz to 1.5g at 20 Hz</p> <p>1. Subjective tolerance data specified from Parks and Snyder (1961)</p> <p>2. Counters read in 32 ft. illumination, 6 to 24 min. of visual angle subtended at 28 inch viewing distance</p> <p>3. Numbers 12 to 24 min. in size found relatively insensitive to vibration</p> <p>4. Counter sizes less than 12 minutes of visual angle were a factor</p> <p>5. 12 to 23 Hz most sensitive range of frequencies - the authors speculate that a sharp deterioration at 12 Hz may be related to CFF (note, however, the relatively bright illumination level)</p>																	
<p>Up to 2.5g (short exposures)</p> <p>Various g's for 1 and 3 minute exposure durations</p> <p>Various g's for each of 4 levels (duration varied across S's)</p> <p>Acceleration levels as indicated in frequency columns (task sequence exceeded 1 minute, exact times not specified)</p>																	
<p>5</p> <p>15</p> <p>7</p> <p>9</p> <p>8</p>																	

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### 5. REQUIREMENTS FOR ADDITIONAL RESEARCH

Requirements for research identified in the present study consist of two general types: requirements to fill gaps in the current body of knowledge, and requirements to evaluate the effectiveness of recommended approaches at reducing identified adverse effects of vibration. Specific requirements are identified in appropriate sections of this report and are summarized here in the description of an integrated helicopter vibration research program. As described on the following pages, this program consists of 12 general studies. Study 1 is designed to meet the most critical need identified in the present investigation, that of obtaining vibration data from a wide range of helicopters performing various missions and of varying age and time since overhaul. Studies 2 through 6 and Study 12 are directed toward the evaluation of techniques for reducing adverse effects of vibration while studies 7 through 11 are aimed at providing data currently unavailable or questionable concerning effects of vibration on helicopter crew performance and biomedical status.

#### STUDY 4. EVALUATION OF SEAT/RESTRAINT DESIGN

Problem: On the basis of findings reported in the present study it is concluded that the effects of vibration on crewmen are aggravated in some cases by inadequate seat/restraint system design.

Objective: To systematically evaluate the effectiveness of modifying seat/restraint system parameters relieving the adverse effects of vibration.

Methodology: The same methodology will be used in this study as described in Study 3, "Evaluation of Vibration Isolation Techniques".  
Seat/restraint system parameters to be varied include:

- Seat design including contour, size, side support, leg support
- Headrest, foot rest, arm rest design
- Seat adjustment and control type, location, force requirements, detents, range of motion
- Seat adjustment forward, backward, up, down, and tilt
- Restraint type, location, resistance to body forces

Crewmen will perform preselected maneuvers under varying configurations of seat/restraint systems and performance data will be recorded.

Measures: Crew performance measures for critical operations.

Expected Results: Identification of the degree to which changes in seat/restraint systems reduces the degrading effects of vibration on performance.

## STUDY 1. INFLIGHT VIBRATION DATA RECORDING

Problem: Critical need for quantitative description of the vibration environment.

Objective: Collect vibration data on representative Navy/Marine Corps helicopters in the field in operational environments.

Methodology: Record, either onboard or via telemetry, vibration spectra data for a wide range of helicopters of varying age and time since last overhaul.

Measures: Vibration frequency and amplitude data over time.

Expected Results: This study should lead to an adequate description of the helicopter vibrational environment and the degree to which the environment varies as a function of different helicopters, helicopter age, time from last overhaul, and missions and mission operations.



## STUDY 2. DEVELOPMENT OF HELICOPTER SPECIFIC CONTROL/DISPLAY REQUIREMENTS

### Problem:

Helicopter controls and displays are generally the same as those used in fixed wing aircraft, which may not be adequate for the rotary wing craft.

### Objective:

To develop requirements for controls and displays specific to helicopters and helicopter missions.

### Methodology:

Develop the list of helicopter crew operations and sequence of operation for specific missions.

Determine the information and performance requirements associated with each operation.

Determine the effect of the environment on performance capability, including vibration, noise and lighting.

Develop design criteria for controls and displays required for the performance of each operation.

Design criteria for displays include:

- Display type (e.g. use of electronic and optical displays)
- Size
- Lighting
- Color coding
- Location with respect to other displays
- Character size
- Rates of motion
- Scaling
- Relation to controls
- Symbology
- Display integration and sharing

- Response lags - quickening

Representative control design criteria include:

- Handling qualities
- Breakout forces
- Detents
- Shape coding
- Extent of movement
- Direction of movement
- Location with respect to displays
- Location with respect to other controls
- Response dynamics

Expected Results: Guidelines for design of helicopter specific controls and displays and required characteristics of these components as derived from operational requirements.

### STUDY 3. EVALUATION OF ISOLATION TECHNIQUES

- Problem: Several techniques of vibration isolation have been proposed. The effectiveness of these techniques must be established.
- Objective: To evaluate the adequacy of vibration isolation approaches.
- Methodology: In Study 2 the effects of the vibration environment on performance of specific operations and on crewman biomedical status were identified. This study will attempt to determine acceptable limits of vibration and will evaluate the effectiveness of isolation techniques in reducing the vibration to a value within the limits.
- Measures: Vibration parameters pre and post isolation measured at various locations of the crewmen's seat and body.
- Expected Results: The effectiveness of isolation techniques in reducing the adverse effects of vibration. This effectiveness must be expressed in terms of requirements for vibration attenuation.

#### STUDY 4. EVALUATION OF SEAT/RESTRAINT DESIGN

Problem: On the basis of findings reported in the present study it is concluded that the effects of vibration on crewmen are aggravated in some cases by inadequate seat/restraint system design.

Objective: To systematically evaluate the effectiveness of modifying seat/restraint system parameters relieving the adverse effects of vibration.

Methodology: The same methodology will be used in this study as described in Study 3, "Evaluation of Vibration Isolation Techniques".  
Seat/restraint system parameters to be varied include:

- Seat design including contour, size, side support, leg support
- Headrest, foot rest, arm rest design
- Seat adjustment and control type, location, force requirements, detents, range of motion
- Seat adjustment forward, backward, up, down, and tilt
- Restraint type, location, resistance to body forces

Crewmen will perform preselected maneuvers under varying configurations of seat/restraint systems and performance data will be recorded.

Measures: Crew performance measures for critical operations.

Expected Results: Identification of the degree to which changes in seat/restraint systems reduces the degrading effects of vibration on performance.

## STUDY 5. EVALUATION OF HELMET MOUNTED DEVICES

Problem: One element of the helicopter display problem is the situation in which the vibrating crewman must abstract information from a display which is also vibrating.

Objective: To determine the effectiveness of helmet mounted devices to display operational information to the pilot.

Methodology: For information reception crew functions degraded by vibration, as determined in Study 2, the feasibility of using helmet mounted devices to display the information will be established. Tests will be conducted to compare crewman performance with the device and with conventional helicopter displays.  
Independent variables include:

- field of view
- monocular or binocular
- information to be presented, frequency, accuracy requirements, etc.
- illumination level
- display characters and figures
- character size

Measures: Time to perform and accuracy of performance of selected information reception functions.

Expected Results: The effectiveness of helmet mounted devices in reducing the degrading effects of vibration.

## STUDY 6. INTEGRATED COCKPIT DESIGN

- Problem: While several of the approaches recommended for reducing the degrading effects of vibration may be more or less effective, the integration of these approaches and its effectiveness must also be established.
- Objective: Determine the collective efficiency of several helicopter design modifications on crew performance capability and biomedical status.
- Methodology: Feasible approaches for reducing the effects of vibration will be evaluated simultaneously by varying parameters of each approach and noting the effect of the composite on performance and physiological well being. This study could be conducted in a laboratory setting or in actual helicopters.
- Measures: Crewman performance and biomedical data.
- Expected Results: This study should provide guidelines for display design when helmet mounted devices are also used, when seat/restraint systems are modified, and when vibration isolation techniques are employed. The impact of other approaches on the effectiveness of each will then be established. Findings from this study may indicate that isolating the vibration alone is insufficient, or that redesign of controls and displays solves the performance problems.

## STUDY 7. LABORATORY EXPERIMENTS - EFFECTS OF VIBRATION

Problem: Too little is presently known concerning the effects of multi-axis vibration, of frequencies and amplitudes found in in-service helicopters, on the performance capability and biomedical status of flight crews.

Objective: To determine, through controlled laboratory experimentation, the effects of representative helicopter vibration on crewmen.

Methodology: Investigate, in a lab setting, the effects of helicopter vibration on:

- display reading ability
- tracking ability
- decision making capability
- accuracy of control
- incidence and degree of fatigue
- performance of helicopter emergency operations
- performance of complex helicopter maneuvers
- short term biomedical status
- long term biomedical status

Investigate the interactive effects of vibration and other stressors (noise, photic stimulation, temperature, fumes).

Investigate the effect of duration of exposure to helicopter vibration.

Investigate the use of vibration as a cue to helicopter malfunction.

Measures: Visual performance  
Decision making performance  
Control accuracy  
Accuracy of completing maneuvers within time constraints  
Biomedical measures

Expected Results: Data defining helicopter crewman performance capability and limitations and biomedical well being - which data will supplement and update the findings of the present study establishing the requirements for reducing or overcoming the adverse effects of vibration and other stressors.



## STUDY 8. FIELD TESTS - EFFECTS OF VIBRATION

Problem: While the laboratory situation provides a quick and relatively inexpensive approach to establishing the effects of vibration, data derived from these studies must be validated by field trials.

Objective: To empirically validate laboratory results through the use of actual helicopter flights.

Methodology: Acquire data on crew performance and biomedical status in the actual helicopter situation. Compare these data with findings reported in laboratory studies.

Measures: To the extent possible, the same measures as used in laboratory studies.

Expected Results: Verification of laboratory data or development of a field factor to correct the lab findings.

## STUDY 9. DEVELOPMENT OF CREW MONITORING PROCEDURES

Problem: Means are required to detect long term effects of vibration on individual crewmen and to assist in the diagnosis of the effects as vibration induced.

Objective: To develop a helicopter crewman tracking and monitoring system.

Methodology: Requirements for records and record formats will be developed to enable flight surgeons to identify vibration induced degradation. Determination of the information to be included in these records comprises the goal of the study. Representative information could include:

- Flight data - number, duration, frequency of flights
- Performance data recorded in periodic performance tests
- Physiological data recorded in periodic biomedical tests
- Diagnostics for isolating degradation to vibration

The frequency of periodic tests and specification of tests to be employed also constitutes a goal of this study.

## STUDY 10. UPDATE OF MIL-H-8501A

Problem: MIL-H-8501A, which indicates acceptable limits of vibration in terms of frequency and acceleration is in need of revision and update. Its scope should be increased to include exposure duration within the various tolerance regions.

Objective: To provide all information necessary for the update of this specification.

Methodology: Data derived from studies 1 through 8 will be compared with standards set forth in the specification. Where discrepancies exist consideration will be given to updating the MIL spec data to agree with the study data. Criteria for selection of data to be added to or deleted from the specification will also be developed.

Expected Results: Quantitative, empirically derived data will serve as a basis for validating or updating vibration frequency and amplitude limit criteria. Moreover, this data should provide a basis for specifying exposure durations within the tolerance regions.

## STUDY 11. DEVELOPMENT OF MAINTENANCE PROCEDURES

Problem: Used helicopters can be made to retain near minimal initial vibration levels if proper maintenance is exercised. The effectiveness of fleet maintenance in controlling vibration is not known.

Objective: Determine the effectiveness of improved maintenance procedures on reducing the vibration environment.

Methodology: Maintenance procedures which could significantly reduce the vibration environment will be identified, such as implementation of blade tracking. Feasible approaches will be incorporated in the maintenance of helicopters of varying type and age and vibration frequencies and amplitudes will be measured at selected points in the cockpit.

## STUDY 12. UPDATE OF CONTROL/DISPLAY REQUIREMENTS

- Problem: As additional data are obtained concerning the effects of vibration on crewmen and on the effectiveness of approaches to reduce adverse effects of vibration, the helicopter control/display design criteria must be updated.
- Objective: To update control/display requirements developed in Study 2.
- Methodology: Identical to Study 3 with the inclusion of additional data derived from Studies 3 through 8.
- Expected Results: Revised control/display design criteria which reflect requirements of helicopter operations which take into account the constraints imposed by the flight environment.

## SECTION 1

## INTRODUCTION

At the present time, a wealth of experimental evidence is being accumulated which describes the effects of various vibration regimes on human performance and biomedical status. Concurrently, there is a substantial increase in helicopter flying and a growing awareness of the potential harm inherent in exposure to the helicopter environment. Unfortunately, much of the empirical research data have not been related specifically to helicopter operation, nor have these data been verified by medical and accident histories of flight crewmen. For these reasons, a systematic review and analysis of significant findings in the research literature, and of interacting variables impinging on those exposed to helicopter operating conditions is somewhat overdue. These, therefore, are the goals of the present study.

We have chosen to focus on vibration as a point of entry into an admittedly broad and complex problem area for several reasons. First, vibration is a fundamental characteristic of all rotary wing aircraft. Second, it has been traditionally difficult to abate or even to attenuate. Third, its physical components are measurable and can be compared to the causes of degraded performance found in a variety of laboratory settings.

However, vibration is by no means the only culprit of concern, nor is it necessarily the most formidable. It is merely one of an array of troublemakers in need of corrective action. Improper seat design, high ambient noise and temperature, inadequate ventilation and cockpit lighting, severe work/rest cycles, and poor instrumentation are some of the others. In addition to these, and perhaps the most evasive of all, is fatigue. This problem is both cause and effect, often subsuming constituent malefactors under its guise.

The above topics and others are cited in Table 1, page 11; the listed subjects represent a composite sample of problems which are assumed to be prevalent in helicopter operations. The table is based on responses from seven independent military facilities, consisting of three Naval hospitals, three Naval air stations, and one Air Force base.

Inspection of the table suggests that fatigue is one of a number of serious problems, and further, that there are several independent variables which may act either alone or in concert to cause fatigue. However, when collective action

is suspected, it is often quite difficult to determine which of the agents may be causing the most severe performance degradation. In fact, it is possible that synergistic effects may be at work and that no single factor can or should be singled out as the primary debilitating agent. Speculation about such matters serves mainly to underscore the complexity facing us and the magnitude of the research task which lies ahead.

The balance of Table 1 indicates that the range of considerations is, indeed, broad, including both specific and more general problem categories. Individual topics contained in the table will be treated throughout the report, in keeping with the scope of work and when the subject matter requires comment. Since most of the quotes in Table 1 are self-explanatory, they need not be commented on further at this time.

We have thus far suggested that helicopters create multi-dimensional problems and that these are widely recognized by a representative sample of cognizant users. Turning now to one of these problems, the effects of vibration on crewmembers, our concern is to systematically develop existing materials so that the relationships among related topics are made clear, and so that gaps in our knowledge become visible.

The most logical prerequisite to an evaluation of the literature on vibration is to describe the vibration characteristics of contemporary helicopters. This is accomplished in Section 2. Here, dominant main rotor frequencies and harmonic peaks are discussed, and evidence suggesting acceleration levels at those frequencies is presented. These data provide a basis for analyzing the literature on vibration research, enabling us to concentrate on those studies treating the most relevant parameters.

In Section 3, our concern is to describe the tasks of pilots and crewmen who are engaged in those helicopter missions which are most important to the Navy and Marine Corps. The treatment afforded this area progresses from the general to the more precise, so that missions, tasks, and aircraft can be evaluated within the proper contextual setting.

Section 4 reduces the number of behaviors described in the preceding section to a manageable number of common categories and facilitates the translation of research findings into terms applicable to the helicopter situation. The behaviors underlying specific procedures are identified in order to isolate perceptual-motor performance requirements and to establish the duration, frequency, and complexity of the performance.

Based on the developed data, qualitative estimates of the susceptibility of mission tasks are made.

Under the heading, Equipment Analysis, our concern shifts to specific subtopics of equipment design which are likely to influence both the effects of vibration and an assessment of the criticality of vibration. For example, seat design and the development of vibration isolation techniques may have impact on the magnitude of vibration ultimately experienced by aircrew members. On the other hand, the trend toward sophisticated electronic devices, such as helmet-mounted displays, suggests that presently experienced vibration levels may have an even more severe impact on the tasks to be performed while using such equipment.

Finally, Section 6 discusses the duration of exposure likely to be experienced by helicopter crewmen and the implications of such exposure on MIL-H-8501A and on the recently published International Organization for Standardization recommendations.



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Helicopter Vibration Characteristics

From the outset we are faced with two general tasks. The first is to describe helicopter vibration characteristics and the concomitant vibration parameters to which aircrew members are routinely exposed. Second, relevant research findings must be described, summarized, and related to the defined exposure conditions. More recondite matters, such as duration of exposure, seat attenuation, and work/rest cycles are deferred for treatment in following sections.

Helicopter vibration characteristics of interest include frequency, displacement amplitude, acceleration amplitude, and direction. Of these, frequency is the easiest to delineate and predict. It is a function both of rotor RPM (1/rev) and the number of blades (usually referred to as either n/rev or b/rev). It will be shown that helicopter frequency patterns exhibit definite peaks at 1/rev, n/rev, and n/rev harmonic frequencies. Amplitude data, on the other hand, are more difficult to characterize. The problem comes not so much from difficulty of measurement, but rather, from a lack of available information. Even the existing in-flight recorded data are sometimes difficult to obtain. Further, available data seldom encompass varied maneuvers, flight segments, or current direction of force measures. One problem is that such data have not been systematically gathered across the helicopter spectrum. Another is that existing data are sometimes given proprietary status by airframe manufacturers. Nevertheless, some useful data are available and will be presented herein. These samples and the guidance afforded by MIL-H-8501A will be used to suggest the vibration environment to which aircrew members are characteristically exposed.

MIL-H-8501A

Section 3.7 of MIL-H-8501A is as follows:

" 3.7 Vibration characteristics.

3.7.1 In general, throughout the design flight envelope, the helicopter shall be free of objectionable shake,

vibration, or roughness. Specifically, the following vibration requirements shall be met:

- (a) Vibration accelerations at all controls in any direction shall not exceed 0.4 g for frequencies up to 32 cps and a double amplitude of 0.008 inch for frequencies above 32 cps; this requirement shall apply to all steady speeds within the helicopter design flight envelope and in slow and rapid transitions from one speed to another and during transitions from one steady acceleration to another.
- (b) Vibration accelerations at the pilot, crew, passenger, and litter stations at all steady speeds between 30 knots rearward and V-Cruise shall not exceed 0.15 g for frequencies up to 32 cps. From V-Cruise to V-Limit the maximum vibratory acceleration shall not exceed 0.2 g up to 36 cps, and a double amplitude of 0.003 inch for frequencies greater than 36 cps. At all frequencies above 50 cps a constant velocity vibration of 0.039 fps shall not be exceeded.
- (c) Vibration characteristics at the pilot, crew, passenger, and litter stations shall not exceed 0.3 g up to 44 cps and a double amplitude of 0.003 inch at frequencies greater than 44 cps during slow and rapid linear acceleration or deceleration from any speed to any other speed within the design flight envelope.

3.7.2 The magnitude of the vibratory force at the controls in any direction during rapid longitudinal or lateral stick deflections shall not exceed 2 pounds. Preferably, these vibratory forces shall be zero.

3.7.3 The helicopter shall be free from mechanical instability, including ground resonance, and from rotor weaving and flutter that influence helicopter handling qualities, during all operating conditions, such as landing, takeoff, and flight."

Although MIL-H-8501A sets forth general acceleration limits both for steady speed and speed change conditions, it is understandably silent on the permissible duration of exposure within the tolerance region. Indeed, MIL-H-8501A itself requires validation and periodic review in keeping with the development of closer approximations to vibration exposure criteria. This topic will again be broached when the subject of International Organization for Standardization (IOS) exposure guidelines are discussed in Section 6. For the present, it will suffice to note that duration of exposure criteria should be based on consideration of a number of variables, including: crewmember tasks, prior exposure history, individual susceptibility, and physical condition. However, our first concern is to outline the anatomy of helicopter vibrations.

#### Frequency, Displacement Amplitude, and Acceleration Amplitude

The helicopter vibration frequency spectrum ranges from about 3 to 110 Hz, having dominant peaks in the 10 to 30 Hz region. Typical helicopter rotor speeds and frequencies are given in Table 5. This summary is adapted from an unpublished

TABLE 5 TYPICAL HELICOPTER ROTOR SPEEDS AND FREQUENCIES

HELICOPTERS STUDIED		SUMMARY OF TYPICAL HELICOPTER CASES				
		PARAMETER	GROSS WEIGHT (lb)			
			2000	6500	10000	100000
BELL	OH-4A, UH-1B, UH-1D, Uh-1F, AH-1G	No. of Blades	2	2	3	6
HILLER	OH-5A	Motor Speed	413	297	262	136
HUGES	CH-6A,XV-9A	f <sub>-</sub> /rev (cps)	6.9	4.95	4.4	2.3
KAMAN	UH-2A	f <sub>N</sub> /rev (cps)	13.7	9.90	13.1	13.8
LOCKHEED	XH-51A	f <sub>2N</sub> /rev (cps)	27.5	19.80	26.2	27.6
SIKORSKY	HH-52A, SH-3A,	f <sub>3N</sub> /rev (cps)	41.3	29.70	39.3	41.4
	CH-3C, CH-53A,	f <sub>4N</sub> /rev (cps)	55.1	39.60	52.4	55.2
	CH-54A					

(from Schuett, 1967)

report by Schuett (1967), reflecting in part the results of his investigation of fifteen turbine-powered single rotor helicopters. Table 6 from Calcaterra and Schubert (1968) supports Schuett's summary, indicating typical weights, RPMs, and b/rev frequencies.

TABLE 6 VALUES OF BLADE PASSAGE FREQUENCY (b/rev) AS A FUNCTION OF HELICOPTER GROSS WEIGHT FOR TYPICAL NOMINAL ROTOR SPEEDS AND NUMBER OF BLADES

GROSS WEIGHT (lb)	ROTOR SPEED (rpm)	NUMBER OF BLADES	BLADE PASSAGE FREQ (Hz)
2,000	400	2	13.3
2,000	400	4	26.6
10,000	200	4	17.7
20,000	214	5	17.9
40,000	194	6	17.5
80,000	145	6	14.5
80,000	145	7	16.8

(from Calcaterra and Schubert, 1968)

In the same report Calcaterra and Schubert show the relationships among levels of rotor-induced vibrations at the blade passage frequency (b/rev) and its harmonics (Figure 1). These data are typical and they indicate the dominant role of b/rev frequencies at the lower end of the helicopter frequency spectrum.

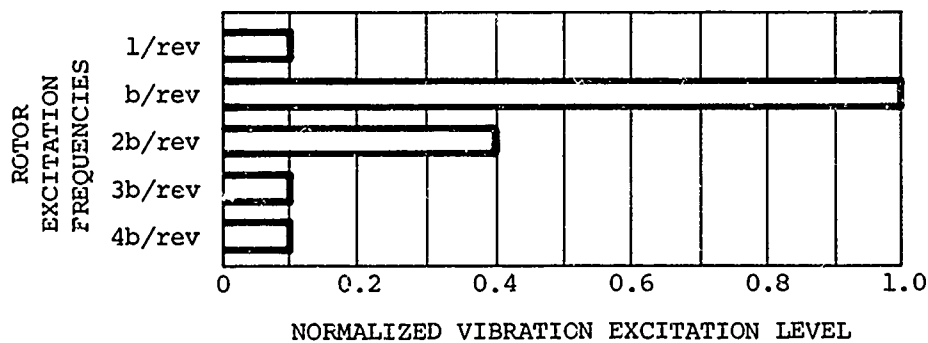


FIGURE 1 RELATIONSHIPS AMONG LEVELS OF ROTOR-INDUCED VIBRATION AT THE BLADE PASSAGE FREQUENCY (b/rev), AND ITS HARMONICS NORMALIZED WITH RESPECT TO THE LEVEL AT b/rev

(from Calcaterra and Schubert, 1968)

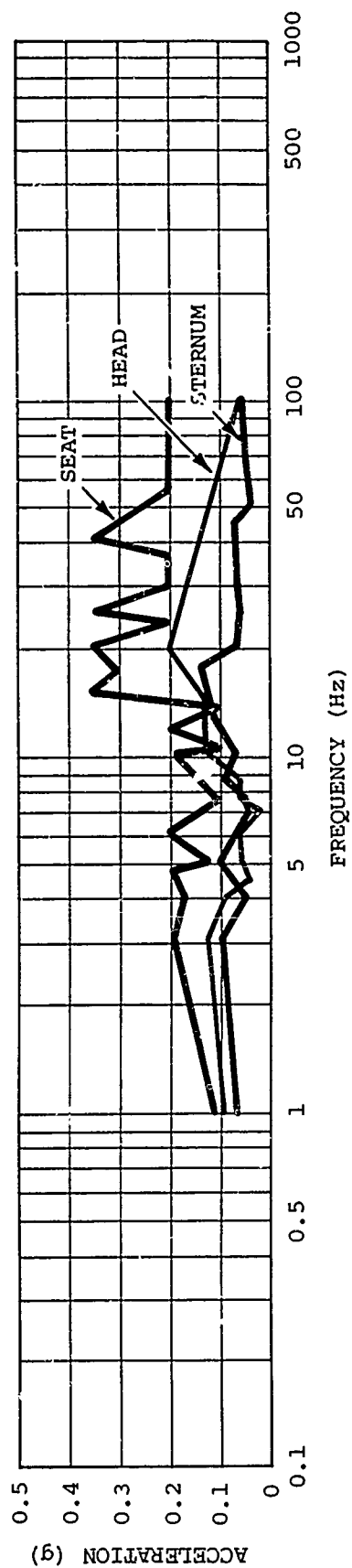
In addition to frequency, two other important characteristics of sinusoidal vibration are displacement amplitude and acceleration amplitude. The former is expressed as maximum half-wave (single amplitude) or full-wave (double amplitude) displacement in inches or centimeters. Acceleration (inches/second<sup>2</sup> or centimeters/second<sup>2</sup>) is the second time derivative of displacement and ordinarily is expressed as maximum or peak g (Roth and Chambers, 1968). In their report, Roth and Chambers discuss the derivation of frequency, displacement amplitude, or acceleration amplitude for sinusoidal vibration when two of the three are known.

One of the few reports which provide x, y, and z axis acceleration and frequency data is that presented by Seris and Auffret (1967). Figures 2a thru 2f are a reproduction of their findings.

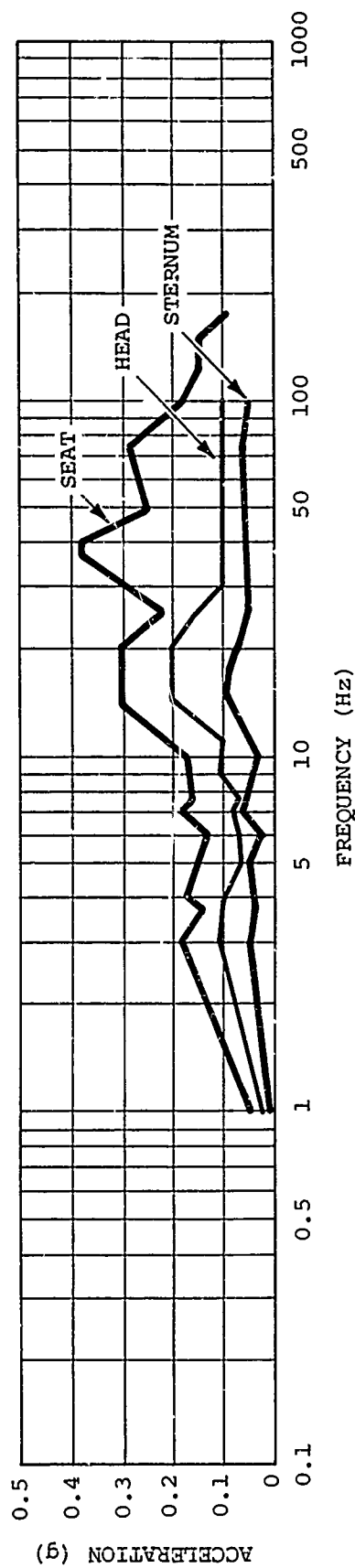
The Seris and Auffret (1967) data were recorded from a Super Frelon 6-bladed, turbine-powered helicopter. Although pilots consider this helicopter to exhibit low vibration, it can be seen that acceleration peaks in the .3 to .5 g region are experienced in all three axes at the main rotor dominant frequency, 20.2 Hz. However, above 15 Hz the acceleration is well damped by the seat and the pilot's body. The authors advise that the low frequencies, 3 to 7 Hz result in maximum discomfort and are the most difficult to dampen.

For comparison, Seris and Auffret note that the frequency spectrum of the Alouette II (3-blades) shows peaks at 6 and 16 Hz and the Sikorsky S58 (4-blades) at 3.7 and 15 Hz. Such data underscore the frequency specific and spiked nature of helicopter vibrations; indicating the desirability of vibration isolation at selected frequencies.

The nature of helicopter vibration characteristics has relevance for considerations relating to methods for isolating vibration. These are discussed in Section 5 where it is shown that the suitability of one of the leading passive techniques is based in part on its effectiveness in minimizing the main rotor dominant spike.



2a Axis Z bearing 260 km/hr



2b Axis Z turn to the right

FIGURE 2 ACCELERATION AND FREQUENCY DATA

(from Seris and Auffret, 1967)

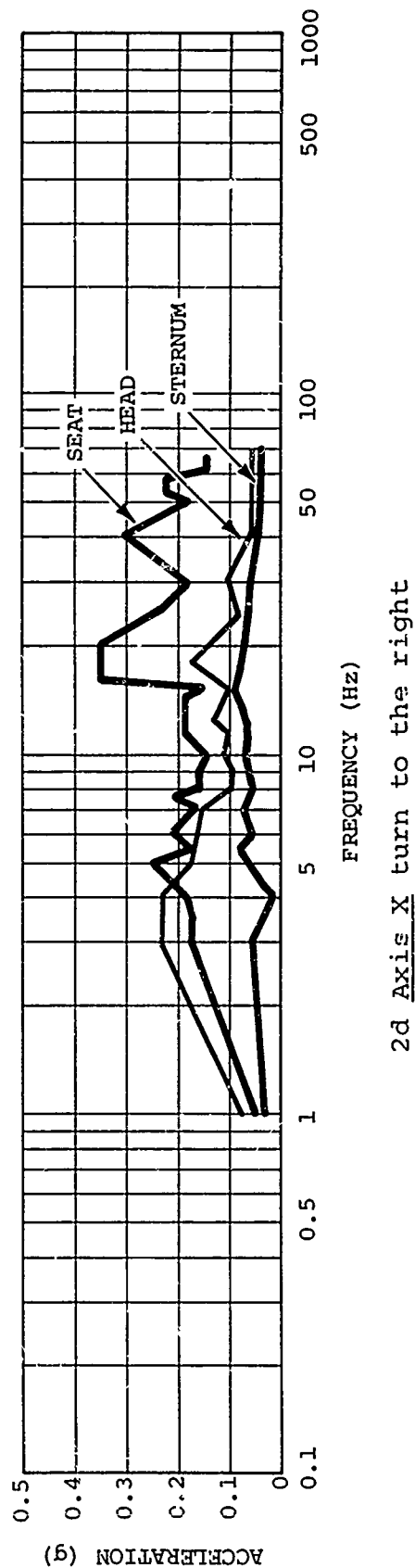
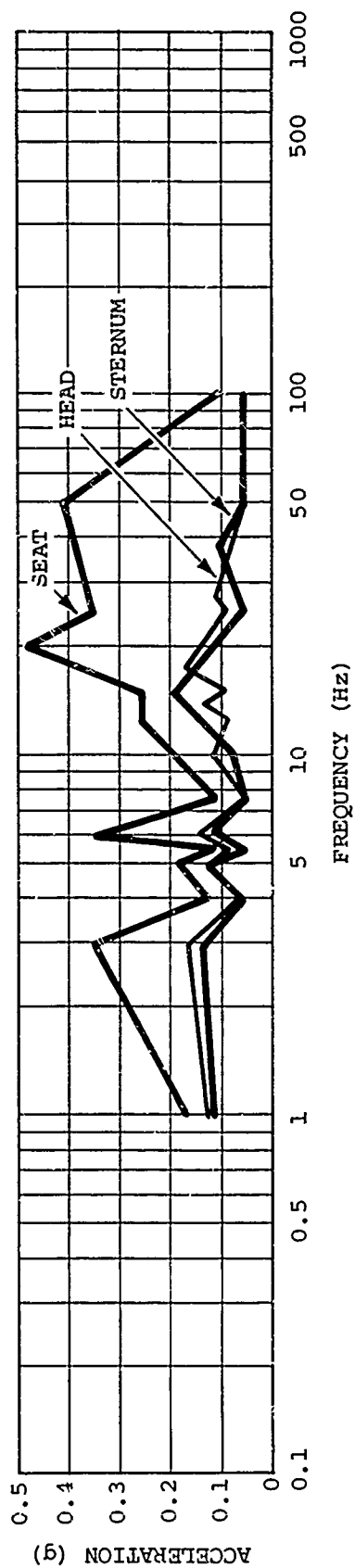
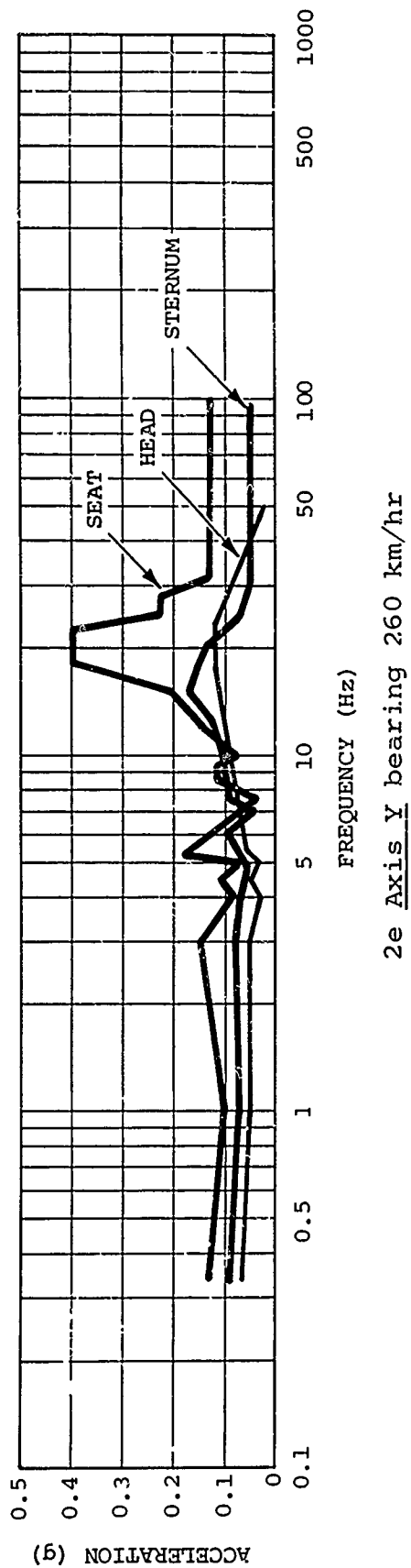


FIGURE 2 (cont)

(from Seris and Auffret, 1967)





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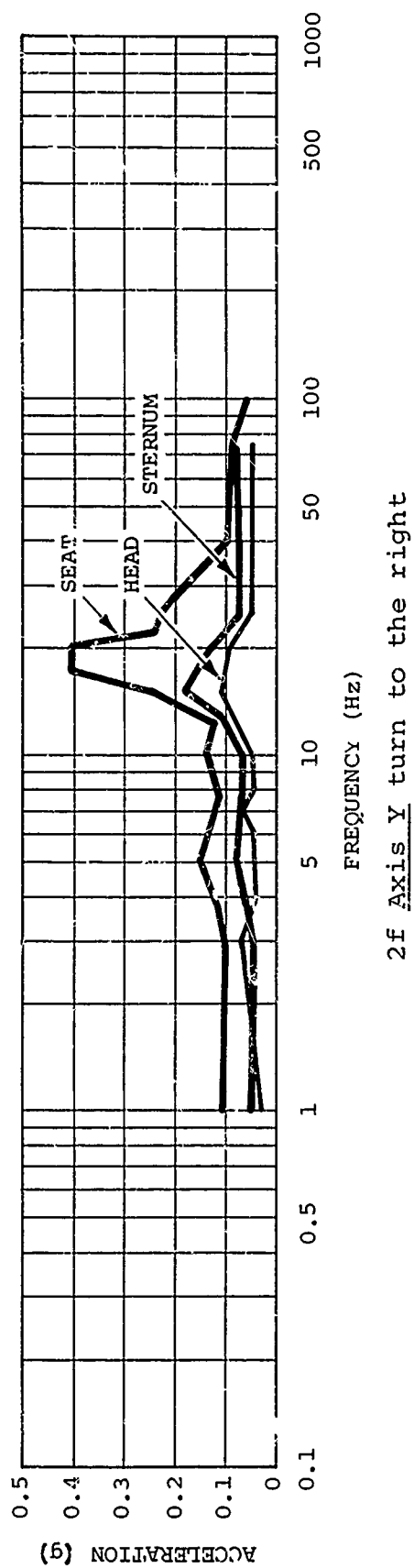


FIGURE 2 (cont)

(from Seris and Auffret, 1957)

## Airspeed vs. Acceleration Amplitude

Data samples suggest that vibration acceleration tends to peak as a function of airspeed and that cruise speeds can be recommended which minimize vibration. Figure 3, for example, indicates data recorded in an exploratory program for the development of the high speed AAFSS (Advanced Aerial Fire Support System). The test vehicle in this case was the 16 H-1A, Pathfinder, a 3-bladed, turbine-powered, compound helicopter. Its performance was tested over a level flight range of zero to 167 knots and at dive speeds up to 195 knots.

Of particular interest is the peak in acceleration between 20 and 40 knots and the constantly increasing curvature above 100 knots. A pattern of this type is not uncommon, although specific values may differ across aircraft. The significance of such data is apparent if one considers that an acceleration peak at about 30 knots is in the region of interest for aircraft carrier recovery operations (i.e. plane guard duty). A fire support mission, on the other hand, is more in keeping with the AAFSS design. In this case high speed dashes to the combat zone would indicate frequent crew exposure to maximum acceleration at the other end of the curve.

Meyers and his colleagues (1968) note that the third harmonic (b/rev depicted in Figure 3 ) meets MIL-H-8501A requirements between 50 and 120 knots. However, the third harmonic slightly exceeds the limit in the range 130 to 155 knots and in the transition range of 20 to 45 knots. At one point, (in a 195-knot 10 degree dive), a third harmonic component of 0.55 g was obtained.

## Vibration and Helicopter Aging

The foregoing are drawn from varied sources, and are offered as samples of typical frequency and acceleration spectra appearing in the literature. Deeper probing would undoubtedly uncover additional material for constructing more refined parameters. However the bulk of such data would probably originate from in-flight tests made at the airframe manufacturers' facility, and might tend to bias our sample rather than enhance its validity. As indicated below, the problem in using such data arises from their suitability, not their veracity.

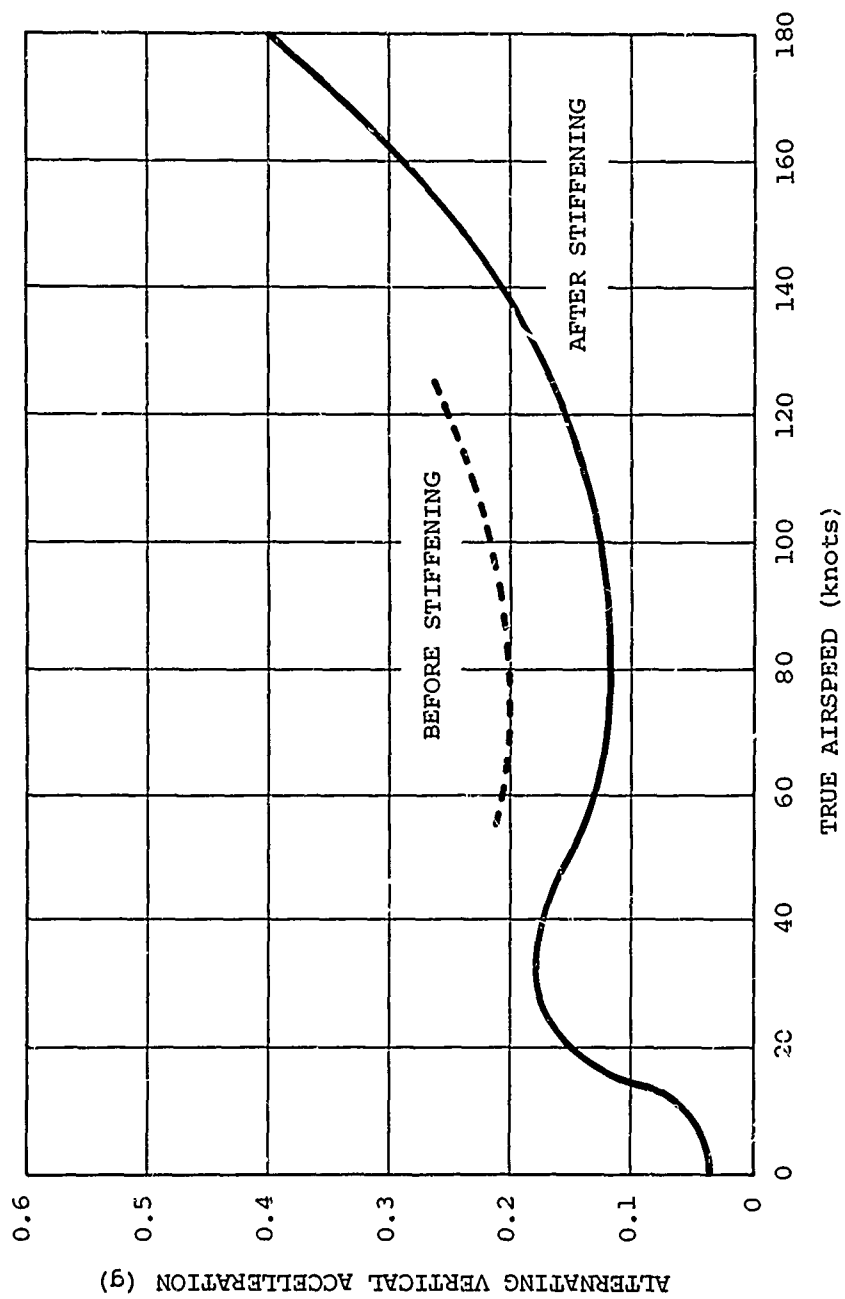


FIGURE 3 THIRD HARMONIC VERTICAL ACCELERATION AT PILOT STATION VS. TRUE AIRSPEED

(from 16H-1A Flight & Test Research Program)

We have thus far suggested that dominant rotor frequencies typically occur in the 10 to 30 Hz region, that peak acceleration is often encountered between 0.2 to 0.4 g's, and that mission airspeed requirements are likely to influence the g-levels actually experienced by aircrew members and, hence, permissible duration of exposure. Acceleration curves from the airframe manufacturers would probably afford little better data with which to refine our initial approximations, because they typically are taken from mint-fresh aircraft and may not represent a characteristic vibration environment.

Our fundamental problem can be summed up in this question -- will the acceleration curves recorded from new aircraft match those from similar aircraft after a period of exposure to field conditions? If not, how much disparity exists at various points in the maintenance cycle and across a representative sample of maintenance facilities? Information on this topic is essentially nil; yet, the issue is of prime importance. Unless adequate data are collected, the actual vibration exposure levels to which aircrew members are subjected will remain uncertain. Moreover, MIL-H-8501A cannot be properly validated in the absence of such data. If, for example, one year of field use characteristically results in a 20 per cent increase in vibration acceleration for a class of helicopters, specification limits should be fixed with this in mind. Similarly, maintenance and operational practices should be tempered by such findings.

Informed helicopter experts recognize the problem, advising that used helicopters can be made to retain near minimal initial vibration levels if proper maintenance is exercised. By "proper" they mean comparable to that available at the manufacturing facility. However, knowing the variety of maintenance facilities, practices, and personnel which exist across the strata of military sites, they are understandably reluctant to speculate on the actual results. In fact, they would probably welcome empirical data in this area for their own guidance. Unless such data are gathered, it is impossible to estimate the severity of the problem.

### Research Findings

This part of Section 2 focuses on selected vibration research findings, emphasizing those within the range of helicopter frequencies and acceleration levels. Our goal is to demonstrate relationships, areas of coverage, research gaps, and trends, and not to conduct a rigorous analysis of the entire gamut of vibration research.

Physiological effects are summarized in Table 2, page 13. Performance effects and subjective tolerance data are presented in Tables 3 and 4, on pages 14 and 21, respectively. Research reports listed under the former depict the frequencies at which body resonances and painful phenomena occur. These are comparatively well established and are revealing when correlated with performance effects, the primary area of interest.

Performance effects are grouped according to major tasks under the following headings.

- o visual acuity
- o dial and number reading
- o complex mental tasks
- o tracking
- o decimal input device operation

While these categories are admittedly a matter of convenience, they do conform to main task descriptions furnished by originating authors and contain subtopics which are themselves of considerable interest. Reaction time, warning light monitoring, pattern recognition, and multiple and random axis vibration are examples of important tasks and conditions which are subsumed under the principal categories. Even so, the data indicate the emphasis in vibration research and allow us to relate experimental results to helicopter main rotor effects.

The third area tabled is subjective tolerance data. Cited reports exemplify attempts to relate subjective evaluations of vibration frequency and acceleration to specified tolerance limits. As one might expect, low subjective tolerance correlates with whole body resonance in the 4 to 8 Hz range. However, at higher frequencies performance degradation may result from eye, head, and facial tissue resonances. In this event subjective acceptability obviously should not govern. Nor, for that matter, should adequate performance be the sole criterion.

#### Performance Effects

In many areas it is difficult to extract reliable generalizations from the vibration research literature. Four problems are immediately apparent. First, experimental conditions,

methodology, and findings are diverse, thereby making extrapolation tenuous. Second, variability of response to vibration across subjects is notoriously wide. Third, the number of subjects per experiment tends to be small. Fourth, experimenters are understandably reluctant to expose subjects to vibration for long durations. Long exposure effects data are therefore, quite rare. However, before discussing general and pervasive difficulties, some specific observations about the tabulated data are in order.

### Visual Acuity and Dial Reading

Vision is by far the most important sense modality. It is of vital concern to helicopter crewmembers and is often the focal point of vibration research experiments.

Physiological data indicate that there are a wide assortment of body resonance frequencies which degrade visual acuity. Head, eye, and facial tissue resonant frequencies extend from about 13 to 80 Hz, some investigators suggesting an even broader range. Hornick (1962) maintains, "Visual acuity suffers in the range 5 to 90 cps and shows decrement related to specific frequencies at 15, 30, and 40-70 cps."

It is, of course, more difficult to specify those acceleration levels which mark the beginning of visual performance degradation. Although there are examples of acceleration effects at various g-levels, the more recent studies suggest that precision of prediction is largely dependent on specific conditions. Task loading and complexity, multiple axis vibration factors, and duration of exposure have only recently been given serious attention in vibration research, and are now beginning to undergo systematic study.

Rubenstein and his associates (1967, 1968) have investigated visual acuity under both z and y-axis exposure conditions and at g-levels ranging from 0.1 to 3.6 g. Even at 5, 8, and 11 Hz, frequencies which are below the critical head resonance region, a constant level of 0.6 g (for 15 minutes) produced decrements in performance. One of their more interesting findings confirms the earlier work of Oshima (1962). Decrements in acuity caused by target vibration are less than decrements caused by head vibration. Also of interest is their method of specifying acuity in terms of the required contrast needed to detect line segment offset, rather than the usual method of fixed contrast and varied target visual angle. In the range 13 to 78 Hz, they found acuity poorest between 22 to 34 Hz, squarely within the region of head resonance.

Examples of other reports dealing with visual acuity include the following. Hornick (1961) reports decrements in visual performance following (but not during) exposure to a maximum of 0.35 g within the range of 0.9 to 6.5 Hz. In a different setting, using printed numbers (under 0.1 ft L of ambient light), Dennis (1956) investigated the range 5 to 35 Hz. He found a 21% increase in reading errors at 0.5 g acceleration. Taub's study (1964) clearly indicates that within the 0.3 to 2.4 g acceleration range a difficult dial reading task produces significantly greater errors than an easy task.

These and other examples of findings in the vibration research literature suggest that helicopter crewmember visual performance is likely to be degraded by vibration within the dominant main rotor frequency range, 10 to 30 Hz. The degradation is likely to be more pronounced as a function of task difficulty, g-level, and work load. Moreover, it is also logical to assume that general crewmember fatigue, resulting from long duration exposure and the effects of temperature, noise, uncomfortable seats, or similar factors, will further degrade visual performance.

#### Tracking and Complex Mental Tasks

In helicopters and in high performance fixed wing aircraft, demands on the pilot are substantial. Increased capability for weapon delivery, and for marginal weather and night operations require more efficient sensors and displays merely to keep abreast of advancing requirements. Within this framework it is often difficult to decide at which point simple tracking performance is replaced by complex mental tasks as the paramount consideration.

Tracking has traditionally been a measure of pilot performance, requiring such psychomotor and cognitive skills as eye/hand coordination, concentration, dynamic sensitivity and awareness. Moreover, tracking has face validity with the use of such primary flight instruments as simple attitude indicators and more complex vertical situation displays. Although these are basically tracking devices, the trend toward integrated electronic displays tends to broaden their original purpose into a more comprehensive multi-modal role. This, in turn, underscores the conclusion that the breadth of pilot performance requirements goes beyond that of simple psychomotor tracking. Visual acuity, information processing, vigilance,

target identification, reasoning, short term memory, decision-making, and similar mental processes take on added meaning as a result of the increased capability afforded by more flexible display devices.

Certainly, resolving mental tasks is not exclusively confined to pilot functions. All crewmembers may be engaged in such activities during the performance of their duties. The copilot, sonar operator, gunner, medical corpsman, and others may be assigned critical responsibilities requiring skill, concentration, and coordination. Regardless of the particular circumstances and sequence of events, such measurable tasks as vigilance, reaction time, and visual performance are certain to be required of the crewmen. Fortunately, these have been treated in a number of vibration research studies.

Harris and Shoenberger (1965) summarized the results of tracking performance research reported in five vibration studies which cover the frequency range below 20 Hz. They noted the diversity of methodology and results and properly cautioned that generalizations from such data are risky, if not wholly unwarranted. The authors suggest, however, that tracking performance is more likely to be affected around whole body resonance, 3-8 Hz. Further, their summary indicates that severe performance effects have been found in the 0.15 to 0.5 g acceleration level region. This range spans limitations specified in MIL-H-8501A and lies above the 0.08 g Long Term Tolerance Curve for Military Aircraft (WADC). We will discuss the problem of duration of exposure in Section 6. For the present, it suffices to note that experimental results indicate performance decrements within the range of helicopter acceleration experience.

Subsequent laboratory work by Harris and Shoenberger (1966) indicates significant tracking performance decrements occurring at 0.2 g (5 Hz), 0.25 g (7 Hz), and 0.37 g (11 Hz). It is interesting that two of their ten subjects reported pain during the 15-minute 5 Hz experiment, one at 0.2 g, the other at 0.25 g. This finding may, of course, merely reflect the wide subject variability noted earlier and emphasize the risk of generalizing too freely from a small sample. Other investigators have not reported pain under similar conditions.

In a more recent study, Lovesey (1968) used similar g-levels in an investigation of the independent and combined effects of multiple axis vibration. Although details are lacking, he found that at the low frequencies studied, y-axis vibration (sway) is more degrading at 0.2 g than z-axis vibration (heave) at 0.25 g. Further, the worst case of those



investigated was 0.25 g at 2 Hz (z-axis) combined with 3.5 Hz (y-axis). These data indicate that the combined vibration effects characteristic of rotary wing aircraft should not be ignored.

Random vibration effects have been studied by Holland (1966), Hornick and Lefritz (1966), and Weisz, Goddard, and Allen (1965). These investigators have used relatively complex experimental designs, which include consideration of such important variables as task loading, reaction time, and vigilance. The two most recent of these studies also introduce exposure duration conditions of 4 and 6 hours. Holland found an improvement in tracking performance during the second and sixth hours; while Hornick and Lefritz report that all 10 subjects could have withstood an additional 2 hours of exposure without detriment.

Weisz and his colleagues, using shorter exposure times, compared the results of random vibration with that of sinusoidal at 5 Hz. They report that significant tracking decrements first appeared at the lowest level of sinusoidal vibration tested, 0.035 g at 5 Hz. For random vibration at the same frequency, decrements first appeared at higher levels. 0.106 and 0.177 g.

Commenting on differences between random and sinusoidal vibration, and similarly, on the direction of applied force, von Gierke (1965) had this to say.

"For lateral vibrations the equivalent tolerance or comfort levels are usually reported as being lower than for vertical vibrations by a factor of 0.7 to 0.5. Similarly the corresponding root mean square (RMS) value for random type broad band vibrations appears lower than the same rating for the RMS value of the sine waves by a factor of approximately 0.6. With respect to these corrections differences of opinion are not pronounced."

If one assumes that subjective responses to vibration are in general accord with performance decrements, this evaluation compares favorably with Lovesey's (1968) finding on the performance effects of lateral vibration (sway). However, it seems counter to Weisz's report of performance decrements at a lower g-level for sinusoidal vibration. The reason for this apparent disagreement is not clear. It may simply be that, although random vibration is subjectively less

tolerable, performance decrements are more pronounced for sinusoidal vibration at some frequencies. Holland (1966) notes, "the relationship ... between human performance during sinusoidal vibration and the performance of operators experiencing typically random operational vibration has never been clearly established."

Shoenberger's (1967) investigation of the effects of vibration on complex mental tasks is one of the few published studies directly aimed at this problem. He found performance decrements in all three of the tasks studied: target identification, warning light monitoring, and probability monitoring. The latter two were statistically significant, but at different frequencies (7 and 11 Hz for the lights; 5 Hz for probability monitoring).

One of the problems to be faced in evaluating the results of complex task experiments is that of priority assignment. Holland (1966) recognized the difficulty when discussing his results by suggesting that "some subjects attend more closely to tracking, while others concentrate on minimizing response time to warning lights." It may well be that statistically significant performance decrements are occasionally not found for the most difficult task, simply because that task is concentrated on to the exclusion of others.

Another general problem concerns the question of cumulative fatigue effects. The 6-hour duration of exposure reported by Holland (1966) is one of the longest to date. Although markedly longer than those reported by most other investigators, there remains a large gap between his 6-hour exposure and that anticipated for future helicopter flights. In-flight refueling techniques have been reported by O'Briant (1967) who foresees the possibility of non-stop flights lasting up to 18 hours.

#### Research Studies Summary and Conclusions

This section has reviewed selected samples of vibration research, summarizing report findings in three related areas.

- o Physiological effects - emphasizes research aimed at delineating body resonant frequencies.
- o Performance effects - emphasizes studies treating frequencies and acceleration levels believed to be characteristic of contemporary helicopters, as well as those which indicate methodological trends or diversity in task coverage.

- o Subject tolerance data - emphasizes the subjective reactions that humans have to z-axis sinusoidal vibration, the type of vibration which has been most thoroughly studied.

Data in these areas have been structured to highlight the short term performance effects of potential concern to helicopter aircrewmembers. Because of diversity in methodology and findings, characteristically small sample sizes, and the wide variability in response found across subjects, it is difficult to draw reliable generalizations from the literature. Nevertheless, there are some apparent trends that can be identified and some tentative conclusions that can be drawn.

1. Low subjective tolerance to vibration has been reported in the 4-8 Hz area. This relates to whole body resonance, voluntary muscle contraction, abdominal pain, jaw resonance, and respiration difficulty. Acceleration levels found to be mildly annoying for this frequency band are in the range of about .2 to .4 g.
2. In the area of main rotor effects, head resonance, lumbosacral pain, and involuntary muscle tone have been reported. Low subjective tolerances have been found between 8-15 Hz with mildly annoying acceleration reported from about .3 to .9 g.
3. Significant decrements in tracking performance have been reported for sinusoidal vibration at 5 Hz at 0.035 RMS g. Severe performance degradation has also been reported for various tasks in the 0.15 to 0.5 g acceleration region between 1 and 20 Hz. These values are well within the spectrum experienced by helicopter crewmen.
4. Task complexity should not be ignored in evaluating vibration effects.
5. The combined effects of z and y-axis vibration have recently been shown to be more detrimental than either component taken separately.
6. Duration of exposure to random vibration following 4 and 6-hour experiments has not been found significantly detrimental. Spontaneous improvements have been noted during the second and sixth hours.

7. Visual acuity tends to be sensitive to vibration effects, particularly in the 22 to 34 Hz region. This area lies within the head and facial tissue resonant zones.
8. Vigilance is impaired as a function of random vibration.
9. Reaction time may be enhanced, impaired, or relatively unaffected by vibration, depending on the conditions.
10. Y-axis vibration is more detrimental than z-axis vibration in some tracking tasks but is probably less detrimental to peripheral vision.
11. Z-axis vibration of the subject's head is probably more detrimental to visual acuity than similar vibration of the target alone. This effect has been noted at frequencies above 10 Hz.
12. The relationship of performance effects between random and sinusoidal vibration remains uncertain.
13. General fatigue resulting from heat, vibration, noise, repeated daily exposure, and long term overall exposure, has not been studied adequately.
14. The results of maintenance on helicopters are not documented; and, therefore, the actual acceleration forces to which helicopter crewmen are exposed cannot be determined.

### SECTION 3

### NAVY/MARINE CORPS HELICOPTERS AND MISSIONS

This section identifies and discusses current Navy and Marine Corps helicopters and missions. A general introduction to the world of military helicopters is presented in Table 7. This table identifies each helicopter by name, manufacturer, military use, commercial name, and military application. General comments regarding unique characteristics associated with each aircraft are also included. In addition, the total number of each type of helicopter produced for military use is included to indicate the relative importance of each helicopter to the user. The bold printed material in this table denote those helicopters that are of prime concern to the Navy and Marine Corps. These helicopters will be further identified and described in more detail. For example, the size of the crew, the number of passengers and the amount of cargo, the type of rotor system, and the performance characteristics of each helicopter are described and then summarized in Table 7.

#### General Description of Navy/Marine Corps Helicopters

##### Types

Three general classes of helicopters are employed by the Navy and Marine Corps: light, medium, and heavy. These designations primarily relate to the total payload a helicopter carries in the performance of its assigned mission. A light helicopter usually carries a pilot and one other crewmember or passenger. In addition, it may be equipped with light armament such as machine guns. An example of a light helicopter is the Navy Bell UH-13P Sioux (refer to Table 8 ).

The medium helicopter is used in either of two general payload configurations: (1) pilot, copilot, 8-15 passengers and light armament, or (2) pilot, copilot, 2 specially trained crewmen and sophisticated equipment. These helicopters are used to transport personnel over land and sea or to perform other special purpose missions. Typical examples of Navy and Marine Corps medium helicopters are the UH-2C, SH-3D and UH-1E (refer to Table 8).

TABLE 7 GENERAL DESCRIPTION OF MILITARY HELICOPTERS

HELICOPTER VARIATIONS*							OPERATIONAL DATA	
MILITARY HELICOPTER DESIGNATORS	NAVY	MARINE CORPS	ARMY	AIR FORCE	COAST GUARD	COMMERCIAL COUNTERPART	QUANTITY	APPLICATIONS
Bell UH-1 series Iroquois/Huey	UH-1B UH-1E HH-1K	UH-1E	UH-1A; UH-1C; UH-1H; UH-1M YUH-1B	TH-1F UH-1F UH-1H		204B 205B	5900 military a/c at end of 1968; production scheduled into 1972	<ul style="list-style-type: none"> <li>UH-1B: Army's primary armed escort</li> <li>UH-1D: Army's primary tactical transport</li> <li>UH-1E: Marine Corp's carrier-based assault support</li> <li>UH-1F: Air Force missile site support</li> </ul>
Bell AH-1G series Huey Cobra		AH-1J	AH-1G			209 series	<ul style="list-style-type: none"> <li>AH-1G: 530 a/c at end of 1968</li> <li>AH-1J: 10 a/c at end of 1968; production scheduled through 1969</li> </ul>	<ul style="list-style-type: none"> <li>Army's interim AAFSS</li> <li>Its prime use is that of an escort for CH-47A Chinook</li> <li>AH-1J is Marine Corps version of Huey Cobra</li> </ul>
Kaman UH-2C Seasprite	UH-2A/B UH-2C						<ul style="list-style-type: none"> <li>UH-2A: 88</li> <li>UH-2B: 96</li> </ul>	<ul style="list-style-type: none"> <li>Navy's primary search and rescue helicopter</li> <li>Other uses: ASW, reconnaissance, supply, carrier plane guard, communications, ship-to-shore transport and casualty evacuation</li> </ul>
Sikorsky SH-3A/D Sea King	FV-3A SH-3A/D	VH-3A	VH-3A	CH-3B/C CH-3E HH-3E	HH-3F	S-61L/N CHSS-2 (RCAP)	652 military a/c at end of 1968; production scheduled through 1972	<ul style="list-style-type: none"> <li>SH-3A/D: Navy's primary ASW helicopter</li> <li>RU-3A: Naval minesweeping operations</li> <li>VH-3A: Army/Marine Corps Presidential helicopter</li> <li>CH-3/HH-3 series: Air Force missile site support, space craft recovery, tactical battlefield support, search and rescue, air-to-air refueling</li> </ul>
Hughes OH-6A Cayuse			OH-6A			Model 369 Model 500	1071 military a/c at end of 1968	<ul style="list-style-type: none"> <li>Army Light Observation Helicopter (LOH)</li> <li>Other uses: casualty evacuation, personnel/cargo transport, light attack, and photographic reconnaissance</li> </ul>
Bell OH-13, UH-13 and TH-13 series Sioux	TH-13M/N UH-13P UH-13P	TH-13 UH-13	OH-13E; -13G; -13H; -13K; -13S; TH-13T	UH-13J	TH-13N HH-13Q	47G-series 47J-series 206A Jet Roger	About 2250 military a/c at end of 1969; production scheduled through 1969	<ul style="list-style-type: none"> <li>UH-13P/R: Navy/Marine utility/ferry helicopter</li> <li>OH-13 series: Army liaison observation and evacuation</li> <li>UH-13J: Air Force executive transport</li> <li>HH-13Q: Coast Guard rescue patrol</li> </ul>
Bell OH-58A and TH-57A Sea Ranger	TH-57A		OH-58A TH-57A			206K	OH-58A: 300 military a/c scheduled for production at end of 1968; continued production scheduled through 1972 for a total of 2,575 a/c	<ul style="list-style-type: none"> <li>OH-58A: Army's primary LOH operations</li> <li>TH-57A: Army's Light Training Helicopter role</li> <li>Navy's primary helicopter training</li> </ul>

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The heavy helicopter carries the heaviest payload. It is used to transport fully equipped troops or equivalent weight in litter cases or cargo. The CH-46D, UH-46F and CH-53D are examples of heavy helicopters (refer to Table 8).

Closely allied to the payload requirement is the power requirement. In the past, helicopters were equipped with piston-powered engines but more recently, they are being equipped with turbine-powered engines. As the demands and uses for the Navy/Marine Corps helicopter have increased, it has become necessary to build larger and heavier helicopters powered by twin-turbine engines.

Another factor to be included in the definition of the three general classes of helicopters is the type of rotor system. For example, the AH-1J Huey Cobra is a light helicopter with a two-bladed, single rotor which develops a rotor speed in the range of 294-356 revolutions per minute in the performance of its armed escort mission; whereas the SH-3D Sea King is a medium helicopter with a five-bladed, single rotor which develops rotor speed in the range of 182-222 revolutions per minute to perform the anti-submarine warfare mission.

#### Payload

Payload refers not only to the maximum weight of equipment, cargo or ordnance that a helicopter carries during the performance of its assigned mission, but to the number of passengers and crew as well. For example, the SH-3D Sea King carries a crew of four on its ASW mission (pilot, copilot and two sonar operators) and up to 6500 pounds of ASW ordnance.

#### Approximate Number in Operation

This figure specifies the approximate number of a particular helicopter in service and performing a mission. For instance, Table 8 indicates that 652 SH-3D's are assigned to the Anti-Submarine Warfare (ASW) mission while 184 UH-2C's are assigned to the Search and Rescue (SAR) mission.

TABLE 8 SUMMARY OF NAVY/MARINE CORPS HELICOPTER CHARACTERISTICS

HELICOPTER VERSION	TYPE	PAYLOAD	APPROXIMATE NO. IN OPERATION	PERFORMANCE CHARACTERISTICS
UH-1E	<ul style="list-style-type: none"> <li>Single rotor</li> <li>2 blades</li> <li>295-324 RPM</li> <li>Medium; turbine</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot</li> <li>8-10 passengers</li> </ul>	203	<ul style="list-style-type: none"> <li>Max. Speed: 159 kt</li> <li>Cruise: 143 kt</li> <li>Climb: 2350 ft/min</li> <li>Ceiling: 16,700 ft</li> <li>Range: 184 n m</li> <li>Weight: 8500 lbs</li> </ul>
AH-1J	<ul style="list-style-type: none"> <li>Single rotor</li> <li>2 blades</li> <li>294-356 RPM</li> <li>Light; turbine</li> <li>Cantilevered fixed wings attached</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot/gunner</li> </ul>	10	<ul style="list-style-type: none"> <li>Max. Speed: 137 kt</li> <li>Cruise: 149 kt</li> <li>Climb: -</li> <li>Ceiling: 10,000 kt</li> <li>Range: 159 n m</li> <li>Weight: 9500 lbs</li> </ul>
UH-2C	<ul style="list-style-type: none"> <li>Single rotor</li> <li>4 blades</li> <li>275-287 RPM</li> <li>Medium; twin turbine</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot</li> <li>11 passengers or 1250 lbs. cargo</li> </ul>	184	<ul style="list-style-type: none"> <li>Max. Speed: 186 kt</li> <li>Cruise: 174 kt</li> <li>Climb: 1740 ft/min</li> <li>Ceiling: 17,400 ft</li> <li>Range: 583 n m</li> <li>Weight: 10,200 lbs</li> </ul>
SH-3D	<ul style="list-style-type: none"> <li>Single rotor</li> <li>5 blades</li> <li>182-222 RPM</li> <li>Medium; twin turbine</li> <li>Amphibian</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot; 2 sonar operators and 6500 lbs armament</li> </ul>	652	<ul style="list-style-type: none"> <li>Max. Speed: 170 kt</li> <li>Cruise: 164 kt</li> <li>Climb: 1550 ft/min</li> <li>Ceiling: 10,200 ft</li> <li>Range: 465 n m</li> <li>Weight: 19,100 lbs</li> </ul>
CH/UH-46D	<ul style="list-style-type: none"> <li>Twin rotor</li> <li>3 blades/rotor</li> <li>263-288 RPM</li> <li>Heavy; twin turbine</li> <li>Amphibian</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot; crew chief</li> <li>17-25 troops or 15 litters with 2 medical attendants or 4000 lbs. cargo</li> </ul>	581	<ul style="list-style-type: none"> <li>Max. Speed: 194 kt</li> <li>Cruise: 183 kt</li> <li>Climb: 1580 ft/min</li> <li>Ceiling: 16,500 ft</li> <li>Range: 231 n m</li> <li>Weight: 21,400 lbs</li> </ul>
CH-53 A/D	<ul style="list-style-type: none"> <li>Single rotor</li> <li>6 blades</li> <li>174-192 RPM</li> <li>Heavy; twin turbine</li> <li>Amphibian</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot; crew chief</li> <li>37 fully equipped troops or 24 litter patients or 8000 lbs. cargo</li> </ul>	96	<ul style="list-style-type: none"> <li>Max. Speed: 170 kt</li> <li>Cruise: 150 kt</li> <li>Climb: 1625 ft/min</li> <li>Ceiling: 18,550 ft</li> <li>Range: 223 n m</li> <li>Weight: 35,000 lbs</li> </ul>
AH-56A	<ul style="list-style-type: none"> <li>Single rotor</li> <li>4 blades</li> <li>high-speed; turbine</li> </ul>	<ul style="list-style-type: none"> <li>pilot; copilot/gunner</li> </ul>	16	<ul style="list-style-type: none"> <li>Max. Speed: 290 kt.</li> <li>Cruise: 277 kt.</li> <li>Climb: 3420 ft/min</li> <li>Ceiling: 26,000 ft</li> <li>Range: 761 n m</li> <li>Weight: 16,995 lbs</li> </ul>

## Performance Characteristics

Performance characteristics refer to the operational capabilities and limitations of a helicopter. These characteristics define flight parameters such as maximum speed, cruising speed, rate of climb, maximum range and maximum weight. Referring to Table 8 the SH-3D Sea King has a maximum speed of 170 knots, a cruising speed of 164 knots, a rate of climb of 1550 feet per minute, a ceiling of 10,200 feet, a range of 465 nautical miles and a maximum weight of 19,100 pounds.

## General Description of Navy/Marine Corps Helicopter Missions

There are many different types of missions flown by Navy and Marine Corps helicopters. In 1953, Dorny, Campbell and Channell conducted a survey of the uses of helicopters in the fleet, the various tasks that are performed by helicopter pilots in accomplishing these missions, and the activities engaged in training fleet helicopter pilots. During the survey, they visited representative operational squadrons securing information on the missions and tasks performed by Naval and Marine helicopter pilots. They summarize their findings as shown in Figures 4 and 5 below.

Figure 4 presents the various operational tasks for both utility and anti-submarine squadrons and shows the relative importance of each in terms of the typical proportion of flight hours logged. Typical values are reflected and only a general distinction made for the various tasks. At that time (1953) utility squadrons logged the major share of operational flight hours. Activities of the ASW squadrons were still in the developmental stage. Dorny, Campbell and Channell indicated that ... "It is anticipated, however, that the anti-submarine role of the helicopter will exceed utility demands in the event of global war and as adequate helicopter and all-weather instruments are produced."

Figure 5 presents the various operational tasks for both transport and observation squadrons and shows the relative importance of each at that time in terms of the typical proportion of flight hours logged. Primary strength was concentrated in the transport group. Secondary helicopter strength was consigned to the VMO squadrons where helicopters exist in conjunction with fixed-wing aircraft.

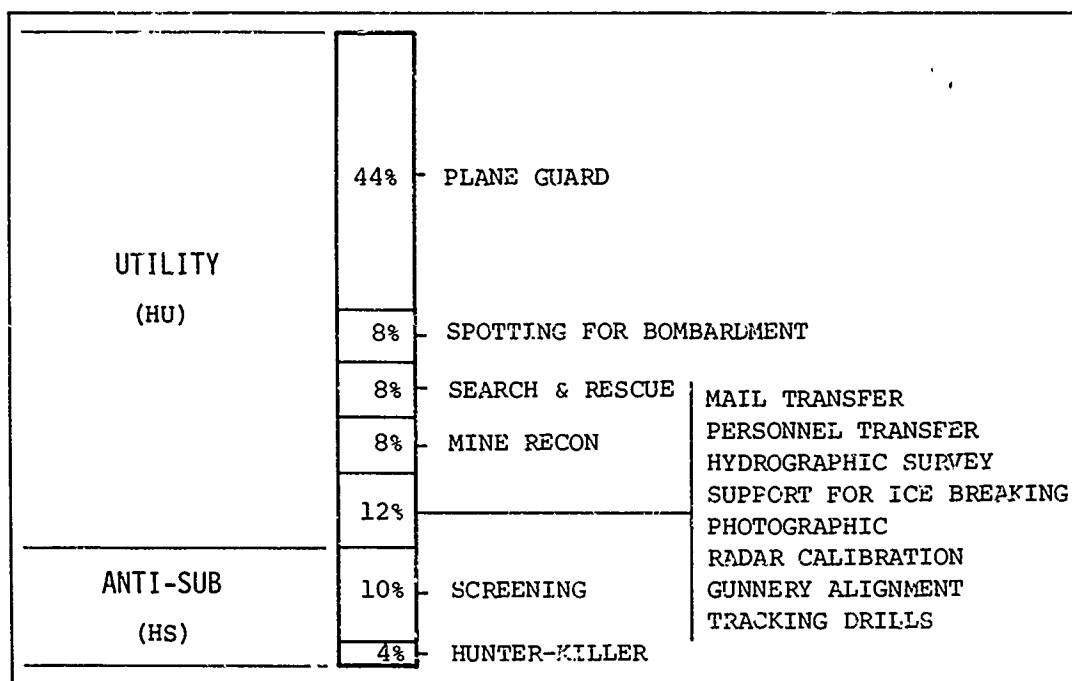


FIGURE 4 PROPORTION OF NAVY FLIGHT HOURS LOGGED BY SQUADRON TYPE AND OPERATIONAL TASK

(from Dorny, Campbell & Channell, Aug 1953)

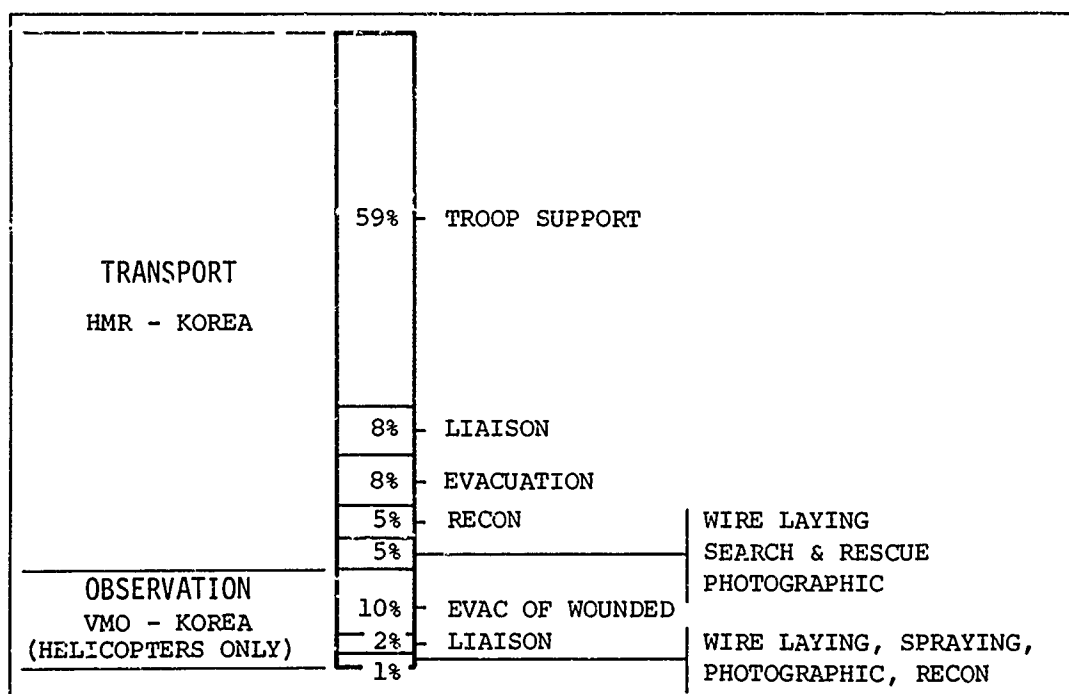


FIGURE 5 PROPORTION OF MARINE CORPS FLIGHT HOURS LOGGED BY SQUADRON TYPE AND OPERATIONAL TASK

(from Dorny, Campbell & Channell, Aug 1953)

"Marine helicopters generally operate from land bases and are integrated in the support of front-line infantry forces. The job of a Marine helicopter pilot has been roughly characterized as 'picking up a load, flying it and setting it down.'"

(Dorny, Campbell, and Channell,  
August 1953)

Similarly, we can identify the Navy and Marine helicopter mission and the number of helicopter types currently assigned to those missions by referring to Table 7. Reference to the QUANTITY column of the table indicates that certain of the helicopters have been produced in significantly greater numbers than some others (these are indicated in dark bold print). For example, 5900 Bell UH-1 series helicopters are being used by the Marine Corps, Army and Air Force in various applications. The Marines use the UH-1E version as their carrier-based assault support helicopter. One hundred eighty-four Kaman UH-2C Seasprites are employed by the Navy as their primary Search and Rescue helicopter. The Seasprite is also used to perform a number of secondary jobs such as ASW, reconnaissance, carrier plane guard, etc. Currently, the Navy has 652 SH-3D Sea Kings assigned as their primary anti-submarine warfare helicopter. By continuing on down the balance of this table and by checking the application of each Navy and Marine helicopter, the reader will have identified the primary helicopter missions as well as the number of helicopter types currently assigned to them.

In 1962, M. D. Havron et al conducted a study for the Office of Naval Research defining the role of helicopters in Army and Navy Missions. They had this to say about types of helicopters:

"The capabilities inherent in the VTOL concept need to be embodied in a relatively few vehicle types. If a vehicle could be designed for just one mission, improved performance in that specific mission might be obtained. But, because there are many missions, each by definition slightly different in requirements, it would obviously be uneconomical to design an aircraft specifically for each. A variety of aircraft types and models renders maintenance complicated and costly, fails to take advantage of low per unit cost of ordering in large numbers, increases problems of

logistics and reduces aircraft availability. For this reason, each service is specifying requirements for a minimal number of different helicopter types. There is some overlap between types and mission requirements but advantages gained by establishing the small number of types is believed to outweigh the consideration that no one type may be optimally adapted to the many possible mission variants."

### Navy Helicopter Mission Requirements

The Navy helicopter mission requirements are clearly indicated in bold print in Table 9. These three missions are Anti-Submarine Warfare (ASW), Search and Rescue (SAR) and Special missions such as Vertical Replenishment and Utility which includes reconnaissance, supply, ship-to-shore transport and casualty evacuation. These three helicopter missions are satisfied by three different types of helicopters, namely, the anti-submarine helicopter, the search and rescue helicopter and the special mission helicopter.

#### Anti-Submarine Warfare Helicopter

The Sikorsky SH-3D Sea King is the primary ASW helicopter. It is equipped with special sonar operations gear as well as a sonar transducer dipping cable. It contains devices to provide precise hovering ability and is capable of day and night, all-weather flights. It can independently launch an attack against enemy submarines or operate as part of an integrated team acting as a sensor for other units in the search and attack group.

#### Search and Rescue Helicopter

The Kaman UH-2C Seasprite is the primary SAR helicopter. It is equipped with a self-contained Radar Navigator System and Automatic Stabilization Gear which enables it to precisely

# TABLE 9 SUMMARY OF NAVY HELICOPTER MISSIONS AND REQUIREMENTS

## SUMMARY OF NAVY HELICOPTER MISSIONS AND REQUIREMENTS

MISSION REQUIREMENT	PRIMARY HELICOPTER ASSIGNED	CREW PASSENGERS CARGO	OPERATION REQUIREMENTS	SPECIAL EQUIPMENT AVAILABLE
Anti-Surface Warfare (ASW)	Sikorsky SH-3D Sea King	<ul style="list-style-type: none"> <li>• Pilot; Copilot; 2 Sonar Operators</li> </ul>	<ul style="list-style-type: none"> <li>• Low altitude precision hovering: sustained periods</li> <li>• Day/night, all-weather capability</li> <li>• Search, detect, identify and destroy enemy submarines unassisted or as part of an integrated team</li> <li>• Cruise speed: 150 kt. dash speed: 200 kt.</li> <li>• Endurance on station: 4 hrs.</li> <li>• Accurate altitude indications to 6,000 feet; for hover, 0 to 40 ft.</li> <li>• Coordinated communications network: helicopter-to-ship</li> <li>• Precise small-area navigation</li> <li>• Ship or shore based</li> <li>• Amphibian</li> </ul>	<ul style="list-style-type: none"> <li>• Hover Indicators; Hover Trim Control</li> <li>• Automatic Stabilization Equipment and Coupler System</li> <li>• Doppler Ground Speed System</li> <li>• Radar Altimeter</li> <li>• Navigation Plotter/Computer</li> <li>• Sonar Detection - Ranging System</li> <li>• Interior/exterior lighting for day/night sonar operations</li> <li>• Sea anchor for light wind drift control</li> <li>• Emergency Flotation Gear</li> <li>• Automatic Blade Folding System</li> <li>• Launching devices for ASW Ordnance</li> <li>• Emergency Sonar Cable Guillotine</li> <li>• Engine Deicing System</li> <li>• Float Cellar Cable Angle Indicator</li> <li>• Pilot/Copilot track - mounted seats with forward, aft and vertical adjustments</li> </ul>
Search and Rescue (SAR)	Kaman UH-2C Seasprite	<ul style="list-style-type: none"> <li>• Pilot; Copilot; 11 passengers or 4 litters or 1250 lbs. cargo</li> </ul>	<ul style="list-style-type: none"> <li>• Utility service capability</li> <li>• Carrier plane guard duty</li> <li>• Liaison and courier transport</li> <li>• Precision hover: up to 7500 ft. alt.</li> <li>• Range: 4 1/2 hrs.; operation radius 200 miles</li> <li>• Cruise speed: 130 kt. max. speed: 145 kt.</li> <li>• All-weather, day/night flts.</li> <li>• Precise navigation</li> <li>• Ship or shore based</li> </ul>	<ul style="list-style-type: none"> <li>• Automatic Stabilization Equipment</li> <li>• Automatic In-flight Blade Tracking System</li> <li>• Rescue Hoist and Boom</li> <li>• Self-contained Radar Navigation System</li> <li>• Navigation Computer/Tactical Display</li> <li>• Shared Electronic Plotting Board</li> <li>• Radar Altimeter/Warning System</li> <li>• Windshield Anti-Icing System</li> <li>• Exterior floodlights for night hoist operations</li> <li>• Passenger Casualty, or cargo carrying equipment</li> <li>• Emergency Flotation Gear</li> <li>• Rotor Deicing System</li> </ul>
Special: Vertical Replenishment and Utility	Boeing-Vertol UH-46D Sea Knight	<ul style="list-style-type: none"> <li>• Pilot; Copilot; Crew Chief</li> <li>• 4000 lbs. cargo</li> </ul>	<ul style="list-style-type: none"> <li>• Larger than Search and Rescue Vehicle</li> <li>• External cargo handling; Vertical resupply of ammunition, stores and supplies to fleet units during maneuvers</li> <li>• All-weather, 24 hr. flight</li> <li>• Range: approx. 5 mi. radius</li> <li>• Ship or shore based</li> </ul>	<ul style="list-style-type: none"> <li>• Three vibration absorbers underneath pilot/copilot seats pre-tuned to dampen 3-per-rev frequency vibration of rotor at 100% RPM</li> <li>• Power Management System</li> <li>• Self-contained Navigation System</li> <li>• Rear-loading Ramp for cargo handling</li> <li>• Integrated Cargo Handling and Rescue System</li> <li>• Automatic Blade Folding System</li> <li>• Passenger Casualty carrying equipment</li> <li>• In-flight Refueling</li> <li>• Stability Augmentation System</li> <li>• Interior/exterior lighting for day/night cargo transport</li> <li>• Engine Deicing System</li> </ul>



track the location of a downed pilot in a minimum of time. Although long range is generally not required on individual search and rescue flights, the capability for longer range missions is available to recover downed pilots discovered at distances from the mother ship. This helicopter is capable of relatively long times on station in the event that it has to await and to complete the rescue. It has a specially designed rescue hoist and boom to retrieve survivors from the sea.

### Vertical Replenishment and Utility Helicopters

The Boeing-Vertol UH-46D Sea Knight is the primary Vertical Replenishment and Utility helicopter. It is equipped to convey materials by external carry for deposit on the ship's deck or it can land on the ship's deck to deposit internal cargo. It is capable of all-weather day and night flights. It contains an Automatic Speed Trim system as well as a Stability Augmentation System enabling the pilot to fly "hands off" when performing other operational procedures.

### Marine Corps Helicopter Mission Requirements

The Marine Corps helicopter mission requirements are clearly indicated in bold print in Table 10. The three missions are Medium Assault Troop Transport, Heavy Transport, and Assault Support. These three missions are satisfied by three correspondingly different types of helicopters, described briefly below.

### Medium Assault Troop Transport Helicopter

The Boeing-Vertol CH-46D/F Sea Knight is the primary Medium Assault Troop Transport helicopter in use today. It has a secondary mission role of cargo transport. It is equipped with a self-contained Navigation System for precise area navigation during all-weather, day and night flights. It contains a Stability Augmentation System for "hands off" flying. It has the capability of operating from floating bases as well as having an amphibious capability. Fully

TABLE 10 SUMMARY OF MARINE CORPS HELICOPTER MISSIONS AND REQUIREMENTS

SUMMARY OF MARINE CORPS HELICOPTER MISSIONS AND REQUIREMENTS

MISSION REQUIREMENT	PRIMARY HELICOPTER ASSIGNED	CREW PASSENGERS CARGO	OPERATION REQUIREMENTS	SPECIAL EQUIPMENT AVAILABLE
Medium Assault Troop Transport	Boeing-Vertol CH-46D Sea Knight	<ul style="list-style-type: none"> <li>• Pilot: Copilot; Crew Chief</li> <li>• 17-25 fully equipped troops or 15 litters with 2 medical attendants or 4000 lbs. cargo</li> </ul>	<ul style="list-style-type: none"> <li>• Troop/cargo transport ship-to-shore during assault operations</li> <li>• Individual flts.: reduced visibility; group flts.: VFR</li> <li>• Max. speed: 130-135 kt.</li> <li>• Range: 100 mn.</li> <li>• Payload capacity: 2 tons, 6000 ft. ceiling</li> <li>• All-weather, day and night flts.</li> <li>• Amphibian</li> </ul>	<ul style="list-style-type: none"> <li>• Three vibration absorbers underneath pilot/copilot seats pre-tuned to dampen 3-per-rev frequency vibration of rotor at 100% RPM</li> <li>• Power Management System</li> <li>• Self-contained Navigation System</li> <li>• Passenger or casualty carrying equipment</li> <li>• Rear loading ramp for cargo handling</li> <li>• Integrated Cargo Handling and Rescue System</li> <li>• Stability Augmentation System</li> <li>• Interior/exterior lighting for day/night troop/cargo transport</li> <li>• Automatic Blade Folding System</li> <li>• Engine Deicing System</li> </ul>
Heavy Transport	Sikorsky CH-53A Sea Stallion	<ul style="list-style-type: none"> <li>• Pilot: Copilot; Crew Chief</li> <li>• 8000 lbs. or 37 fully equipped troops or 24 litters with 3 medical attendants</li> </ul>	<ul style="list-style-type: none"> <li>• Transport weapons, munitions, and combat supplies over land and sea</li> <li>• Payload capacity: 4 tons</li> <li>• All-weather, day and night flts. within 50 to 6000 ft. alt. range</li> <li>• External cargo load carrying</li> <li>• Troop transport capacity: 37 fully equipped troops</li> <li>• Range: 100 mi.</li> <li>• Minimum speed: 130-135 kt.</li> <li>• Casualty evacuation: 24 litter capacity</li> <li>• Amphibian</li> </ul>	<ul style="list-style-type: none"> <li>• Automatic Flight Control System</li> <li>• Special Landing Gear System for confined area operations</li> <li>• Special window/door facilities for cargo/troop transport</li> <li>• Full size opening with a built in ramp for loading and unloading of cargo and personnel</li> <li>• Integrated Interior/Exterior Cargo Handling System</li> <li>• Passenger or casualty carrying equipment</li> <li>• Engine Anti-Icing System</li> <li>• Armor-plate protection for crew, engine and utility hydraulic system</li> <li>• Pilot/Copilot track-mounted seats with forward, aft and height adjustments</li> <li>• Interior/exterior lighting for day/night cargo/troop transport</li> <li>• Automatic Blade and Pylon Folding System</li> <li>• Radar Altimeter</li> <li>• Special Fire Detector Systems</li> <li>• Emergency water landing provisions</li> </ul>
Assault Support	Bell UH-1E Iroquois	<ul style="list-style-type: none"> <li>• Pilot: Copilot/gunner</li> <li>• 8-10 fully equipped troops</li> </ul>	<ul style="list-style-type: none"> <li>• Utility service capability including transporting personnel to battle areas, casualty evacuations from battle areas or ships, emergency supply/resupply, reconnaissance, plane guard and search and rescue</li> <li>• Payload capacity: over 800 pounds or 8-10 passengers</li> <li>• Range: 50 mi. radius</li> <li>• Max. speed: 130-135 kt.</li> <li>• Marginal weather flts.: limited night operations</li> <li>• Precise area navigation</li> <li>• Precise hovering capability</li> <li>• Ship or shore based</li> </ul>	<ul style="list-style-type: none"> <li>• Self-contained Navigation System</li> <li>• Rescue Hoist System</li> <li>• Interior/Exterior Armament Stores</li> <li>• Troop or Casualty Carrying equipment</li> <li>• Armor-plate protection for crew, fuel, and armament stores</li> <li>• Automatic Blade Folding; Pylon Folding</li> <li>• Exterior floodlights for night cargo operations</li> </ul>

equipped troops can be readily boarded through the rear loading ramp in a minimum of time.

#### Heavy Transport Helicopters

The Sikorsky CH-53A Sea Stallion is the primary Heavy Transport helicopter. It has a secondary mission role of Mine Counter Measure. It is capable of transporting weapons, munitions and combat supplies over land and sea to a maximum range of approximately 115 nautical miles. It is equipped with an Automatic Flight Control System enabling it to operate in all-weather, day and night flights from 50 to 6,000 feet altitudes. It uses a special Landing Gear System for confined area operations. It is equipped with a full-sized rear opening with a built in ramp for loading and unloading cargo and personnel.

#### Assault Support Helicopters

The Bell UH-1E Iroquois/Huey is the primary Assault Support helicopter. It is equipped with a self-contained Navigation System for precise area navigation. It can perform precise hovering, and it contains a rescue hoist system, with troop or casualty carrying equipment for use on a variety of utility service missions. It has armor-plate protection for the crew, fuel, and armament stores.

#### General Comments

Tables 9 and 10 summarize the Navy and Marine Corps helicopter missions and requirements. It also specifies the primary helicopter assigned to each mission, the payload, the operation requirements of the vehicle, and the special equipment available to assist the crew in performing the mission functions. We will return to this table again when we resume our discussion on mission analysis.

## Future Operations and Helicopter Missions

Future operations will continue to make ever increasing demands to expand the existing capabilities of the military helicopter. Already, the era of the "shooting" helicopter, brought about by the Vietnam conflict, has created a new role for the helicopter. Future armed helicopters will be required to operate at much faster speeds while carrying heavier and more sophisticated weapon support equipment. There exists a need for a high performance helicopter or advanced Vertical Take Off and Land (VTOL) aircraft for search/rescue/recovery of downed pilots in the Vietnam jungles. Present rescue helicopters lack the range and speed to reach air crews downed deep in enemy territory. A development project is currently under way to remedy this situation. The objective of this project, which is entitled Combat Aircrew Recovery Aircraft (CARA), is to increase the hover performance and speed of rescue vehicles, decreasing reaction time in rescue tasks and increasing the penetration capability of these craft.

The ability of existing helicopters to transport large numbers of fully equipped troops or heavy weapons and combat supplies in support of tactical operations will be further developed, perhaps eventually approaching 60 to 70 tons. Inflight refueling operations are already being used to increase the range of the heavy transport helicopter.

Capt. R. W. Hensen, USNR-R in a recent article in Data Publications discusses the need for a destroyer-based, light, manned helicopter to complement the effectiveness of the destroyer's long range sonar capability. According to Capt. Hensen, present day escort destroyers, although equipped with sonar systems capable of long range detection, do not have an effective weapons system to deploy against these long range contacts. This inability to launch an immediate countermeasure reduces the effectiveness of the destroyer's long range cover system to that of a short range system. Since a few destroyers already have helicopter hangers and platforms, the light, manned helicopter would be one practical solution to the ASW problem.

## Mission Analysis

The foundation for this analysis is contained in Tables 9 and 10. These data are derived from information contained

in the NATOPS flight manuals listed in the bibliography and from several published reports treating helicopter missions and handling requirements. The analysis also reflects information obtained during interviews with Navy helicopter pilots, ASW flight instructors and test pilots at a helicopter manufacturing facility.

A typical profile of each helicopter mission is presented in a pictorial diagram. These diagrams illustrate the distinguishing characteristics of each mission requirement. For example, each profile specifies the following types of data:

1. Typical altitudes flown during the mission,
2. Representative airspeeds at these altitudes,
3. Number of landings required during the mission,
4. Range to each destination from the point of origin,
5. Length of loiter time (inflight or on the ground) at the destination point,
6. Description of the return flight for those missions that terminate at the point of origin, and
7. The geography of the environment i.e., whether the mission is performed over land or sea.

Many different types of tasks are performed by the crew throughout the course of any helicopter mission. However, there are certain critical tasks that are mission-oriented; i.e., "tasks whose performance within some mission-imposed tolerance is a requirement to mission accomplishment." (W. Sardanowsky et al., July, 1968).

How accurately these critical mission tasks are performed by the crew within the constraints of the mission will depend largely upon how suitable their helicopter can perform the mission.

An analysis of the critical mission tasks of the Navy and Marine Corps helicopter missions is presented in Tables 11 through 16.

A.

TABLE 11 ANTI-SUBMARINE WARFARE

MISSION: ANTI-SUBMARINE WARFARE (ASW)

MISSION PHASE: SONAR OPERATIONS AT HOVER

MISSION RESPONSIBILITIES		TIME FACTORS	CRITICAL EVENTS AND SEGMENTS																																				
<p><u>PILOT</u></p> <p>Maintain a stabilized hover 40 feet above the sea for sustained periods while controlling helicopter heading and attitude so that sonar cable remains vertical and motionless underwater.</p> <p><u>COPILOT</u></p> <p>Completes prepip checklist for the first dip; during the dipping cycle, operates various cockpit controls to determine the performance accuracy of the sonar cable angle indicator, radar altimeter and hydrostatic height indicator, and the hover bearing readings of all sonar contacts into navigation computer and marks plotting board for navigation purposes.</p> <p><u>SONAR OPERATORS</u></p> <p>The two crewmen who are responsible for operating the sonar system work in 30-minute shifts. Except for recording duties, the entire sonar operation is controlled by one man. The operator raises and lowers the dome, monitors visual display of search pattern and listens for audible echo return over earphones.</p>	<p>Flight, transition, hover and dip cycle - total time approximately 15 to 20 min.</p> <p>May be required to hover and dip in search area for up to 2 hrs. during a 4 hr. mission</p>	<p><u>PILOT AND COPILOT TASKS</u></p> <p>A. Establish a stabilized hover before lowering sonar cable</p> <ol style="list-style-type: none"><li>1. Null any drift, forward motion, yaw and altitude changes, as required</li><li>2. Cross check performance accuracy on HOVER INDICATOR</li><li>3. Make any necessary corrections</li></ol> <p>B. Maintain stabilized hover during sonar dipping operation</p> <ol style="list-style-type: none"><li>1. Operate mode select knob on HOVER INDICATOR to cable position</li><li>2. Set CYCLE COUPLER toggle on AUTOMATIC STABILIZATION EQUIPMENT CONTROL PANEL to CABLE ANGLE position</li><li>3. Check sonar cable angle on HOVER INDICATOR</li><li>4. Check sonar cable depth by comparing RADAR ALTITUDE and HYDROSTATIC HEIGHT INDICATOR reading. Readings should match within + 5 feet</li><li>5. Cross checks sonar cable depth, as required, by setting ALTITUDE COUPLER toggle on A.S.E. CONTROL PANEL to CABLE ALTITUDE position</li><li>6. Read cable altitude on HOVER INDICATOR</li><li>7. Repeat steps A1 thru A3, as required</li></ol> <p><u>SONAR OPERATOR TASKS</u></p> <p>A. Lower sonar cable upon command from pilot</p> <ol style="list-style-type: none"><li>1. Activate Hydraulic Cable Reeling Machine to reel out cable by operating the following controls on the Sonar Detecting-Ranging Control panel:<ol style="list-style-type: none"><li>a. Move DOME CONTROL-RAISE-LOWER toggle to LOWER position and hold</li><li>b. Monitor DEPTH METER until: correct amount of cable has been lowered</li><li>c. Release DOME CONTROL-RAISE-LOWER toggle to stop cable descent</li></ol></li><li>2. Report cable depth to pilot over Intercommunication System (ICS)</li><li>3. Coordinate steps B1 through B6, as required, by adjusting CABLE ANGLE CONTROL DRIFT knobs to center HOVER INDICATOR vertical and horizontal bars on CREWMEN'S CONSOLE. Visually check cable centered in funnel and report, as required</li></ol> <p>B. Checkout Sonar Detecting-Ranging Control panel and Azimuth/Range Indicator panel for sonar search operations</p> <ol style="list-style-type: none"><li>1. Cycle controls to each position indicated in table below and verify meter readings</li></ol>	<table><tr><th colspan="2">CONTROL/DISPLAY NAME</th><th colspan="4">CONTROL POSITION &amp; DISPLAY READOUT</th></tr><tr><td>OPERATION SELECTOR SWITCH</td><td>CONV</td><td>3</td><td>1</td><td>30</td><td>TEST</td></tr><tr><td>JE SELECTOR SWITCH</td><td>-</td><td>2 to 5</td><td>2 to 5</td><td>5 to 8</td><td>20</td></tr><tr><td>POWER OUTPUT METER</td><td></td><td></td><td></td><td></td><td>-</td></tr><tr><td>LISTEN SECTOR KNOB</td><td></td><td></td><td></td><td></td><td>1 thru 8, ALL</td></tr><tr><td>VIDEO GAIN KNOB</td><td></td><td></td><td></td><td></td><td>Adjust until dots appear in all four sectors of target CRT - barely visible</td></tr></table> <ol style="list-style-type: none"><li>2. Check variable TEST OSCILLATOR LEVEL - FULL CCW<ol style="list-style-type: none"><li>a. Rotate TEST OSC. LEVEL ROTARY - CW until tones audible - Record Reading (45 or greater)</li><li>b. Rotate CW until dots are visible on target CRT - Research Reading (40 or greater)</li></ol></li><li>3. Repeat steps 2a. and b for all eight sectors</li><li>4. Repeat - GO, NO GO STATUS OF EQUIPMENT</li><li>5. Set all panel controls for sonar search operations</li></ol>	CONTROL/DISPLAY NAME		CONTROL POSITION & DISPLAY READOUT				OPERATION SELECTOR SWITCH	CONV	3	1	30	TEST	JE SELECTOR SWITCH	-	2 to 5	2 to 5	5 to 8	20	POWER OUTPUT METER					-	LISTEN SECTOR KNOB					1 thru 8, ALL	VIDEO GAIN KNOB					Adjust until dots appear in all four sectors of target CRT - barely visible
CONTROL/DISPLAY NAME		CONTROL POSITION & DISPLAY READOUT																																					
OPERATION SELECTOR SWITCH	CONV	3	1	30	TEST																																		
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LISTEN SECTOR KNOB					1 thru 8, ALL																																		
VIDEO GAIN KNOB					Adjust until dots appear in all four sectors of target CRT - barely visible																																		

SONAR OPERATORS

The two crewmen who are responsible for operating the sonar system work in 30-minute shifts. Except for recording duties, the entire sonar operation is controlled by one man. The operator raises and lowers the dome, monitors visual display of search pattern and listens for audible echo return over earphones.

B.

- A. Lower sonar cable upon command from pilot
1. Activate Hydraulic Cable Reeling Machine to reel out cable by operating the following controls on the Sonar Detecting-Ranging Control panel:
    - a. Move DOME CONTROL-RAISE-LOWER toggle to LOWER position and hold
    - b. Monitor DEPTH METER until correct amount of cable has been lowered
    - c. Release DOME CONTROL-RAISE-LOWER toggle to stop cable's descent
  2. Report cable depth to pilot over Intercommunication System (ICS)
  3. Coordinate steps B1 through B6, as required, by adjusting CABLE ANGLE CONTROL DRIFT knobs to center HOVER INDICATOR vertical and horizontal bars on CREWMEN'S CONSOLE. Visually check cable centered in funnel and report, as required
- B. Check out Sonar Detecting-Ranging Control panel and Azimuth/Range Indicator panel for sonar search operations
1. Cycle controls to each position indicated in table below and verify meter readings

CONTROL/DISPLAY NAME	CONTROL POSITION & DISPLAY READOUT			
OPERATION SELECTOR SWITCH	COMM	3	30	TEST
RANGE SELECTOR SWITCH	-	1	3	20
POWER OUTPUT METER	2 to 5	2 to 5	5 to 8	-
LISTEN SECTOR KNOB	1 thru 8, ALL			
VIDEO GAIN KNOB	Adjust until dots appear in all four sectors of target CRT - barely visible			

2. Check variable TEST OSCILLATOR LEVEL - FULL CCW
  - a. Rotate TEST Osc. LEVEL ROTARY - CW until tones audible - Record Reading (45 or greater)
  - b. Rotate CW until dots are visible on target CRT - Research Reading (40 or greater)
3. Repeat steps 2a. and b for all eight sectors
4. Repeat -- GO, NO GO STATUS OF EQUIPMENT
5. Set all panel controls for sonar search operations

# TABLE 12 SEARCH AND RESCUE

MISSION: SEARCH AND RESCUE (SAR)		MISSION PHASE: RESCUE OPERATIONS	
MISSION RESPONSIBILITIES	TIME FACTORS	CRITICAL EVENTS AND SEGMENTS	
<p><b>PILOT</b></p> <p>Pass directly over the survivor at a prescribed altitude and airspeed, heading downwind for approximately two miles. Roll out and return in a steady, gradual and controlled descent approach to a hover 20-40 feet above the survivor. Maintain a stabilized hover until the rescue is completed. Climbout from hover to a prescribed altitude.</p> <p><b>COPILOT</b></p> <p>Continuously tracks the helicopter's heading and position in the rescue area on the Tactical Plotting Board. Operates various cockpit controls to provide the Pilot with accurate altitude, airspeed and rate of descent information during all maneuvers. During night operations, illuminates the rescue area by air-dropping electric marking lights.</p> <p><b>RESCUE CREWMAN</b></p> <p>Assists the pilot as an observer, in directing the helicopter over the survivor. Activates, lowers, raises and deactivates the rescue hoist and fishpole equipment. May be required to enter water and attach survivor to rescue sling. During night operations, illuminates the rescue area by air-dropping electric marking lights. Attends to survivor, as required.</p>	<p>Flight, transition, hover and rescue cycle - total time is dependent upon prevailing wind condition at the rescue area.</p> <p>Time at rescue station may vary from 30 minutes to 2½ hours depending on the amount of fuel and the distance to the rescue area.</p> <p>Endurance on station up to 2½ hours maximum.</p>	<p><b>PILOT AND COPILOT TASKS</b></p> <p>A. Adjust flight altitude and airspeed to 200 feet at 60 knots downwind of the hover point</p> <ol style="list-style-type: none"> <li>1. Verify AUTOMATIC STABILIZATION EQUIPMENT (A.S.E.) control engaged</li> <li>2. Check present altitude heading and airspeed on the DIRECTION VELOCITY INDICATOR (DVI). Check attitude on the REMOTE ATTITUDE INDICATOR</li> <li>3. Vary COLLECTIVE PITCH LEVER and CYCLIC CONTROL STICK to attain the required altitude, heading and airspeed.</li> <li>4. Verify MODE KNOB on TACTICAL DISPLAY PLOTTING BOARD set at TRACK position. Operate SCALE KNOB to 10-MILE position</li> <li>5. Cross check performance accuracy on the DIRECTION VELOCITY INDICATOR and the REMOTE ATTITUDE INDICATORS</li> <li>6. Execute a 90-270 degrees standard rate turn</li> <li>7. Make any necessary corrections to stabilize altitude and airspeed</li> <li>8. Track helicopter heading and position on TACTICAL DISPLAY PLOTTING BOARD</li> </ol> <p>B. Establish a steady and controlled descent approach to the hover point (Doppler Approach)</p> <ol style="list-style-type: none"> <li>1. Verify BAROMETRIC ALTITUDE switch - 2AR ALT position</li> <li>2. Pilot RADAR ALTITUDE LIMIT-ON-KNOB - 30 feet</li> <li>3. Copilot RADAR ALTITUDE LIMIT-ON-KNOB - 30 feet</li> <li>4. Set A.S.E. control - RAD ALT to initiate automatic descent</li> <li>5. Monitor rate of descent on DVI</li> <li>6. Trim airspeed, as required, using CYCLIC STICK TRIM SWITCH on CYCLIC CONTROL STICK to arrive at 80 feet with 40 knots. Helicopter levels off at 80 feet</li> <li>7. As descent continues, minor heading corrections should be made with the YAW TRIM SWITCH on the COLLECTIVE PITCH LEVERS. Cross-check airspeed, altitude, and rate of descent on the DVI. Helicopter levels off at 40 feet</li> <li>8. Trim airspeed, as required, using CYCLIC STICK TRIM SWITCH to 30 knots. Survivor should be 1/4 to 1/2 miles ahead</li> <li>9. Throughout approach be prepared to disengage altitude control and take over manually if automatic control does not perform reliably</li> </ol> <p>C. Maintain a stabilized hover 20-40 feet over the survivor during rescue operations</p> <ol style="list-style-type: none"> <li>1. Engage A.S.E. mode control switch - GROUND SPEED</li> <li>2. Monitor DIRECTION VELOCITY INDICATOR and GROUND SPEED DRIFT-ANGLE INDICATOR for ground speed and drift changes</li> <li>3. Trim excess ground speed and drift with the CYCLIC CONTROL STICK and CYCLIC STICK TRIM SWITCH to arrive over survivor at zero ground speed and zero drift</li> <li>4. Cross-check both needles on DVI centered at hover</li> <li>5. HOIST CONTROL switch - ARMED</li> </ol> <p>D. Transition to forward flight after rescue operations complete</p> <ol style="list-style-type: none"> <li>1. Set Copilot RADAR ALTITUDE LIMIT-ON-KNOB - 80 feet</li> <li>2. Trim pitch altitude using CYCLIC CONTROL STICK - nose down to the horizon</li> <li>3. Monitor pitch attitude</li> <li>4. Monitor helicopter's altitude and vertical velocity on DVI for a positive rate of climb</li> <li>5. When airspeed greater than 70 knots: Disengage A.S.E. GROUND SPEED switch - OFF</li> <li>6. Disengage RAD ALT control - depress ALTITUDE CONTROL button on the COLLECTIVE PITCH LEVER</li> <li>7. Manually adjust COLLECTIVE PITCH LEVER to climb power and climb to 300 feet altitude</li> </ol>	



<p>12. Complete climb from hover to a prescribed altitude.</p> <p><b>COPILLOT</b></p> <p>Continuously track the helicopter's heading and position in the rescue area on the Tactical Plotting Board. Operates various cockpit controls to provide the pilot with accurate altitude, airspeed and rate of descent information during all maneuvers. During night operations, illuminates the rescue area by air-dropping electric marking lights.</p> <p><b>RESCUE CREWMAN</b></p> <p>Assists the pilot as an observer, in directing the helicopter over the survivor. Activates, lowers, raises and deactivates the rescue hoist and fishpole equipment. May be required to enter water and attach survivor to rescue sling. During night operations, illuminates the rescue area by air-dropping electric marking lights. Attends to survivor, as required.</p>	<p>Time at rescue station may vary from 30 minutes to 2 1/2 hours depending on the amount of fuel and the distance to the rescue area.</p> <p>Endurance on station up to 2 1/2 hours maximum.</p>	<p>Position: Copilot's ALT knob to 10-mile position velocity indicator</p> <p>5. Cross check performance accuracy on the DIRECTION VELOCITY INDICATOR and the REMOTE ALTITUDE INDICATORS</p> <p>6. Execute a 90-270 degree standard rate turn</p> <p>7. Make any necessary corrections to stabilize altitude and airspeed</p> <p>8. Track helicopter heading and position on TACTICAL DISPLAY PLOTTING BOARD</p> <p>B. Establish a steady and controlled descent approach, to the hover point (Doppler Approach)</p> <p>1. Verify BAROMETRIC ALTITUDE switch - BAR ALT position</p> <p>2. Pilot RADAR ALTIMETER LIMIT-ON-KNOB - 30 feet</p> <p>3. Copilot RADAR ALTIMETER LIMIT-ON-KNOB - 30 feet</p> <p>4. Set A.S.E. control - RAD ALT to initiate automatic descent</p> <p>5. Monitor rate of descent on DVI</p> <p>6. Trim airspeed, as required, using CYCLIC STICK TRIM SWITCH on CYCLIC CONTROL STICK to arrive at 80 feet with 40 knots. Helicopter levels off at 80 feet</p> <p>7. As descent continues, minor heading corrections should be made with the YAW TRIM SWITCH on the COLLECTIVE PITCH LEVERS. Cross-check airspeed, altitude, and rate of descent on the DVI. Helicopter levels off at 40 feet</p> <p>8. Trim airspeed, as required, using CYCLIC STICK TRIM SWITCH to 30 knots. Survivor should be 1/4 to 1/2 miles ahead</p> <p>9. Throughout approach be prepared to disengage altitude control and take over manually if automatic control does not perform reliably</p> <p>C. Maintain a stabilized hover 20-40 feet over the survivor during rescue operations</p> <p>1. Engage A.S.E. mode control switch - GROUND SPEED</p> <p>2. Monitor DIRECTION VELOCITY INDICATOR and GROUND SPEED DRIFT-ANGLE INDICATOR for ground speed and drift changes</p> <p>3. Trim excess ground speed and drift with the CYCLIC CONTROL STICK and CYCLIC STICK TRIM SWITCH to arrive over survivor at zero ground speed and zero drift</p> <p>4. Cross-check both needles on DVI centered at hover</p> <p>5. HOIST CONTROL switch - ARMED</p> <p>D. Transition to forward flight after rescue operations complete</p> <p>1. Set Copilot RADAR ALTIMETER LIMIT-ON-KNOB - 80 feet</p> <p>2. Trim pitch altitude using CYCLIC CONTROL STICK - nose down to the horizon</p> <p>3. Monitor pitch attitude</p> <p>4. Monitor helicopter's altitude and vertical velocity on DVI for a positive rate of climb</p> <p>5. When airspeed greater than 70 knots: Disengage A.S.E. GROUND SPEED switch - OFF</p> <p>Disengage RAD ALT control - depress ALTITUDE CONTROL button on the COLLECTIVE PITCH LEVER</p> <p>6. Manually adjust COLLECTIVE PITCH LEVER to climb power and climb to 300 feet altitude</p> <p>7. Set A.S.E. RAD ALT mode control switch - STANDBY Engage BAR ALT altitude control on COLLECTIVE PITCH LEVER</p>
		<p><b>RESCUE CREWMAN TASKS</b></p> <p>A. Prepare for rescue operations</p> <p>*1. Actuate electric marking lights</p> <p>*2. Open CARGO DOOR and airdrop lights - 5 sec. intervals along downwind leg of rescue pattern</p> <p>3. Don and connect safety harness</p> <p>4. At RESCUE DOOR observe survivor's position</p> <p>5. Assist pilot in directing helicopter over survivor</p> <p>6. Direct pilot to extend boom: BOOM CONTROL switch - EXT</p> <p>7. Check survivor's position</p> <p>8. Direct pilot to lower rescue hoist: HOIST switch - DOWN</p> <p>9. Observe hoist descend to water near survivor</p> <p>10. Direct pilot to position helicopter swinging hoist cable to survivor</p> <p>11. Observe survivor in rescue sling</p> <p>12. Direct pilot to raise hoist cable: HOIST switch - UP</p> <p>13. Open RESCUE DOOR and assist survivor into helicopter</p> <p>14. Disconnect rescue sling from hoist cable</p> <p>15. With hoist cable outside, close RESCUE DOOR</p> <p>16. Assist or place survivor on litter in aft cabin, as required</p> <p>* NOTE: Omit steps 1 and 2 when visibility in rescue area is good</p>

# TABLE 13 VERTICAL REPLENISHMENT

MISSION: VERTICAL REPLENISHMENT		MISSION PHASE: IN FLIGHT VERTICAL REPLENISHMENT DURING SEA MANEUVERS	
MISSION RESPONSIBILITIES	TIME FACTORS	CRITICAL EVENTS AND SEGMENTS	
<p><u>PILOT</u></p> <p>Maintain a stabilized hover over the ship's flight deck while controlling lateral or longitudinal velocity to correspond with the ship's motion. Perform attitude adjustments during the unloading operation to maintain horizontal and vertical alignment over the load. Descend vertically and release the load.</p> <p><u>COPILOT</u></p> <p>Control the helicopter during the hover and unloading operation, as required. Assist the pilot with the load releasing operations.</p> <p><u>CREW CHIEF</u></p> <p>Assists the pilot, as an observer, in directing the helicopter over the flight deck. Informs the pilot when to lower the helicopter toward the deck and when the sling is free of the hooks.</p>	<p>Flight, trans- sition, hover and unloading cycle - total time approx- imately 2-3 minutes de- pending on size of load and distance to delivery point.</p> <p>Mission dura- tion varies from 1-2 hrs.</p> <p>Endurance on station up to 2 hrs.</p>	<p><u>PILOT, COPILOT AND CREW CHIEF TASKS</u></p> <p>A. Establish a stabilized hover relative to the flight deck</p> <ol style="list-style-type: none"> <li>1. Verify Automatic FLIGHT CONTROL SYSTEM engaged</li> <li>2. Null any drift, forward motion, yaw and altitude changes, as re- quired</li> <li>3. Cross checks performance accuracy on AIRSPEED, VERTICAL SPEED, ATTITUDE and TURN AND SLIP INDICATORS</li> <li>4. Make any necessary corrections</li> <li>5. Check status of cargo position with Crew Chief over intercom</li> </ol> <p>B. Adjust lateral or horizontal velocity to maintain hover relative to the flight deck</p> <ol style="list-style-type: none"> <li>1. Move CYCLIC CONTROL STICK, as required</li> <li>2. Periodically check TURN AND SLIP INDICATORS</li> <li>3. Coordinate alignment of load above the flight decks over the intercom with the Crew Chief</li> <li>4. Make any necessary altitude or velocity changes, as required</li> </ol> <p>C. Descend toward flight deck and release load</p> <ol style="list-style-type: none"> <li>1. Check status of Cargo Hook Controls:               <ol style="list-style-type: none"> <li>a. Verify CARGO HOOK circuit breaker - IN</li> <li>b. Set CARGO HOOK MODE SELECT switch - PILOT RELEASE</li> <li>c. Verify amber SAFETY LOCK ON light - illuminated red HOOK OPEN light - extinguished</li> </ol> </li> <li>2. COLLECTIVE PITCH LEVER - PUSH DOWN, as required</li> <li>3. When Crew Chief indicates load on flight decks, pilot/copilot depress CARGO HOOK RELEASE pushbutton on CYCLIC CONTROL STICK</li> <li>4. Verify red HOOK OPEN light - illuminates amber SAFETY LOCK ON light - extinguished</li> <li>5. If light does not illuminate, pull the EMERGENCY RELEASE T-handle to release load sling from cargo hooks</li> </ol>	

TABLE 14 MEDIUM ASSAULT TROOP TRANSPORT

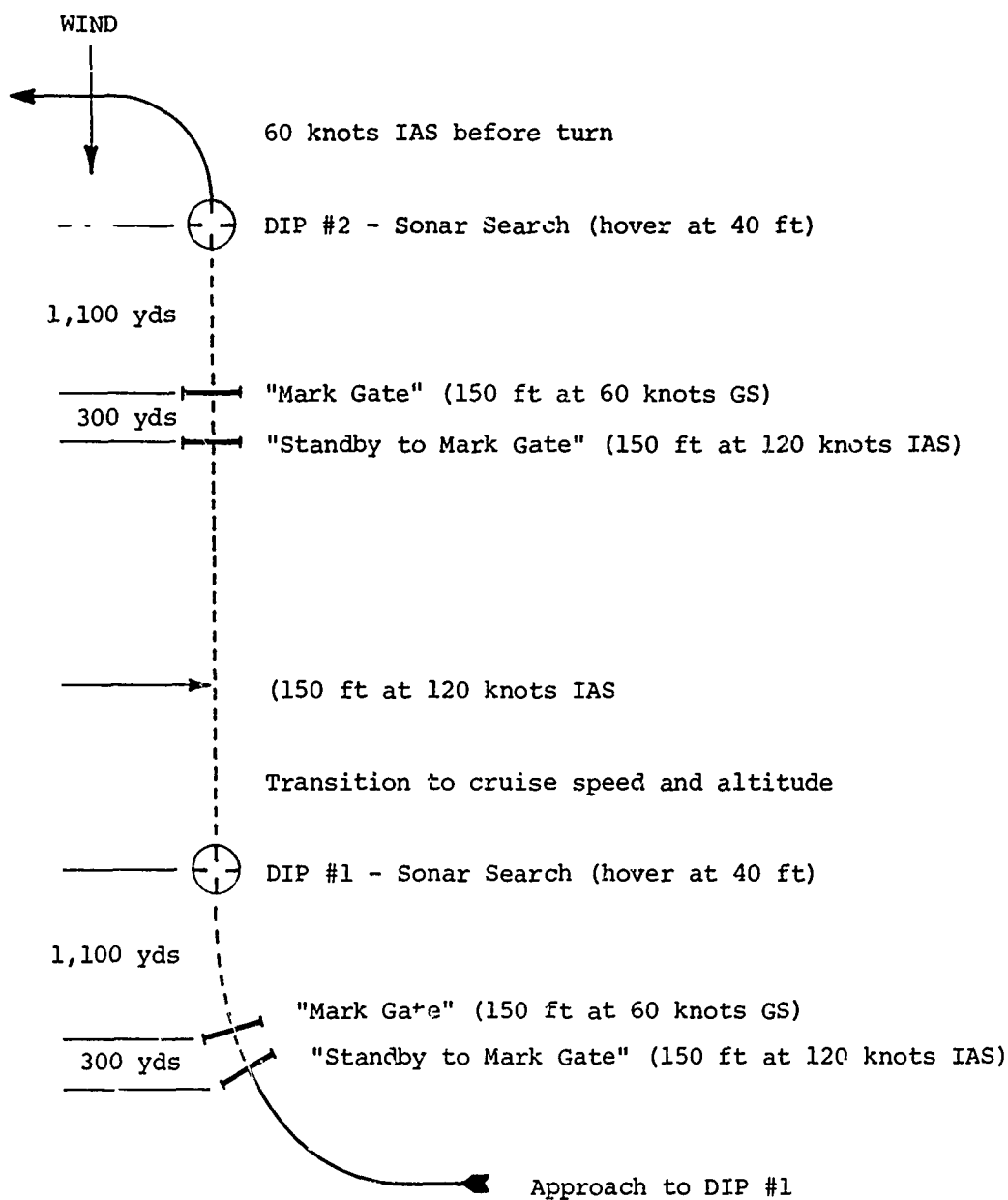
MISSION: MEDIUM ASSAULT TROOP TRANSPORT		MISSION PHASE: LOW ALTITUDE CRUISING OVER JUNGLE TERRAIN DURING NIGHT OPERATIONS	
MISSION RESPONSIBILITIES	TIME FACTORS	CRITICAL EVENTS AND SEGMENTS	
<p><u>PILOT</u></p> <p>Maintain straight and level, low altitude flight under reduced visibility (Instrument Flight Rules) conditions.</p> <p><u>COPILOT</u></p> <p>Continuously tracks the helicopter's flight path to the destination point by relating it to the computer-stored flight path. Monitor actual flight path by operating various cockpit controls. Update computer-stored data at various visual check points to determine when inflight changes are required to reach the destination.</p> <p><u>CREW CHIEF/TROOP COMMANDER</u></p> <p>Assist pilot/copilot, as an observer, when passing over geographic check points.</p>	<p>Cruising duration varies from 20 mins. to one hour depending upon distance to destination and weather conditions.</p> <p>Mission duration up to 2 hours.</p> <p>Maximum time on station up to 2 hours.</p>	<p><u>PILOT, COPILOT AND CREW CHIEF TASKS</u></p> <p>A. Maintain straight and level flight to destination area</p> <ol style="list-style-type: none"> <li>1. Periodically check attitude and lateral deviations from TACAN course on the ATTITUDE DIRECTOR INDICATOR</li> <li>2. Correct any excess pitch and roll - move COLLECTIVE PITCH LEVER, as required</li> <li>3. Cross check engine performance parameters:               <ol style="list-style-type: none"> <li>a. TRIP/TIME TACHOMETER - % ROTOR RPM within limits</li> <li>b. TORQUEMETER - % ENG TORQ NO. 1 and NO. 2 within limits</li> </ol> </li> <li>4. Move COLLECTIVE PITCH LEVER and CYCLIC CONTROL STICK, as required.</li> <li>5. Adjust ENGINE POWER SETTING CONTROLS, when required</li> <li>5. Periodically check attitude and airspeed on BAROMETRIC ALTITUDE, AIRSPEED and VERTICAL SPEED INDICATORS</li> <li>6. Make any necessary corrections using CYCLIC CONTROL STICK, as required</li> </ol> <p>B. Compare computer-stored flight position data displayed on the COMPUTER READOUT panel with actual inflight position data on the MAP PLOTTER DISPLAY, flight instrument readings and visual check points. Make any necessary inflight position changes, as required</p> <ol style="list-style-type: none"> <li>1. Check operational status of flight and navigation equipment - all MODE ADVISORY lamps extinguished</li> <li>2. Using a visual check point determine present position relative to computer-stored position displayed on the COMPUTER READOUT panel               <ol style="list-style-type: none"> <li>a. Insert present coordinate values displayed on MAP PLOTTER DISPLAY into DATA INPUT panel</li> <li>b. Use a visual check point and depress INSERT pushbutton marked ENT</li> <li>c. If data good ENT light will illuminate</li> <li>d. Report steps a through c, setting DATA INPUT-POSITION rotary switch - CP2, CP3, and CP4 before depressing INSERT pushbutton</li> </ol> </li> <li>3. Cross check present position heading and distance to destination point displayed on the ATTITUDE DIRECTOR and BEARING, DISTANCE AND HEADING INDICATORS and the MAP PLOTTER with that stored in the computer               <ol style="list-style-type: none"> <li>a. Set COMPUTER READOUT selection switches, as required, - compare with flight instruments readings</li> </ol> </li> <li>4. Move COLLECTIVE PITCH LEVER, as required, to adjust present inflight position</li> </ol>	

# TABLE 15 HEAVY TRANSPORT

MISSION: HEAVY TRANSPORT		MISSION PHASE: AIRLIFT DOWNED AIRCRAFT TO FLIGHT ALTITUDE	
MISSION RESPONSIBILITIES	TIME FACTORS	CRITICAL EVENTS AND SEGMENTS	
<p><u>PILOT</u></p> <p>Maintain a stabilized hover into the wind line over the downed aircraft until ground crew attaches external cargo hookup. Lift load vertically until clear of ground objects. Transition from hover to forward flight.</p> <p><u>COPILLOT</u></p> <p>Monitor flight control displays during cargo hookup operation. Assist pilot with cargo hookup operation, as required.</p> <p><u>CREW CHIEF</u></p> <p>The Crew Chief is stationed in the cargo compartment to inform the pilot on pickup and status of the load during flight.</p>	<p>Flight, transition, hover and pickup cycle - total time approximately 15-20 minutes</p> <p>Maximum flight endurance of 100 miles radius</p> <p>Endurance on station up to 2 hours</p>	<p><u>PILOT, COPILLOT AND CREW CHIEF TASKS</u></p> <p>A. Establish a stabilized hover over the load</p> <ol style="list-style-type: none"> <li>1. Verify AUTOMATIC FLIGHT CONTROL SYSTEM engaged for hover. Remove feet from ROTARY RUDDER PEDALS</li> <li>2. Null any drift, forward motion, yaw and altitude changes, as required</li> <li>3. Cross check performance accuracy on AIRSPEED, VERTICAL SPEED, ATTITUDE and FLIGHT DIRECTOR INDICATORS</li> <li>4. Make any necessary corrections</li> <li>5. Check the status of cargo position with the Crew Chief over the intercom</li> <li>6. Make any necessary altitude or position change relative to the cargo location, as required</li> </ol> <p>B. Prepare to pickup cargo</p> <ol style="list-style-type: none"> <li>1. Check status of CARGO HOOK Controls:               <ol style="list-style-type: none"> <li>a. Verify CARGO HOOK circuit breaker - IN</li> <li>b. Set STATION SELECT switch - ALL</li> <li>c. Verify CARGO HOOK OPEN light - extinguished</li> </ol> </li> <li>2. AIRCREWMAN PORTABLE PENDANT CONTROL - depress CARGO HOOK OPEN button</li> <li>3. Verify CARGO HOOK OPEN light - illuminates</li> <li>4. When AIR DIRECTOR on ground attaches load slings over the cargo hook load beam</li> <li>5. Set CARGO MASTER switch - SAFE</li> <li>Verify CARGO HOOK OPEN light - extinguished</li> </ol> <p>C. Lift load vertically until clear of obstacles</p> <ol style="list-style-type: none"> <li>1. Crew Chief informs pilot over intercom when ground personnel are clear of immediate area</li> <li>2. COLLECTIVE PITCH LEVER - PULL UP, as required</li> <li>3. When load clear of surrounding obstacles, depress COLLECTIVE STICK TRIM switch - ON and release COLLECTIVE PITCH LEVER</li> <li>4. Hover momentarily and adjust ENGINE SPEED LEVERS to provide sufficient engine power to maintain the load</li> <li>5. CYCLIC CONTROL STICK - FORWARD, slowly climbing to flight altitudes</li> </ol>	

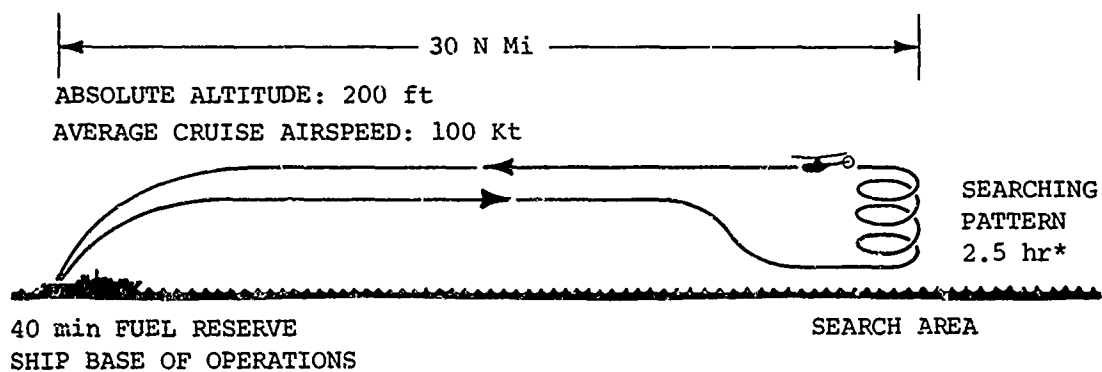
# TABLE 16 ASSAULT SUPPORT

MISSION: ASSAULT SUPPORT (FIRE CONTROL)		MISSION PHASE: NAP-OF-THE-EARTH FLIGHT USING POP-UP TACTICS	
MISSION RESPONSIBILITIES	TIME FACTORS	CRITICAL EVENTS AND SEQUENCES	
<p><u>PILOT</u></p> <p>NAP-OF-THE-EARTH flight taking full advantage of the terrain to gain concealment from enemy observation and fire. Use pop-up tactics to acquire and fire upon enemy.</p> <p><u>AERIAL GUNNER/OBSERVER</u></p> <p>Search track, acquire and fire upon enemy elements. Assist pilot to concealment areas for pop-up tactics.</p>	Endurance up to 3 hours.	<u>PILOT AND AERIAL GUNNER/OBSERVER TASKS</u>	
		<p>A. Pop-up from hover peering over terrain features for enemy elements</p> <ol style="list-style-type: none"> <li>1. COLLECTIVE PITCH LEVER - PULL UP, as required</li> <li>2. Visually search for enemy elements, noting physical location from helicopter position (5-10 seconds)</li> <li>3. Drop down behind cover again; COLLECTIVE PITCH LEVER - PUSH DOWN, as required</li> <li>4. Inform pilot of location of enemy elements</li> <li>5. NAP-OF-THE-EARTH flying to next pop-up location</li> </ol> <p>B. Running pop-up from concealment to fire on target</p> <ol style="list-style-type: none"> <li>1. Trim attitude aligning with target direction</li> <li>2. CYCLIC CONTROL STICK - FORWARD, to climb in forward flight</li> <li>3. Depress machine gun fire button, observe any damage (5-10 seconds)</li> <li>4. Descend behind terrain features using NAP-OF-THE-EARTH flight to next pop-up location</li> </ol> <p>C. Pop-up from hover to fire on target</p> <ol style="list-style-type: none"> <li>1. Trim any drift, forward motion, yaw and attitude, as required</li> <li>2. COLLECTIVE PITCH LEVER - PULL UP</li> <li>3. Peer over terrain features and fire upon enemy elements</li> <li>4. Drop down behind cover or concealment again</li> </ol>	



Next Dip upwind. Command to standby to mark gate allows helicopter time to slow to gate speeds.

FIGURE 6 SONAR DIPPING MISSION PROFILE



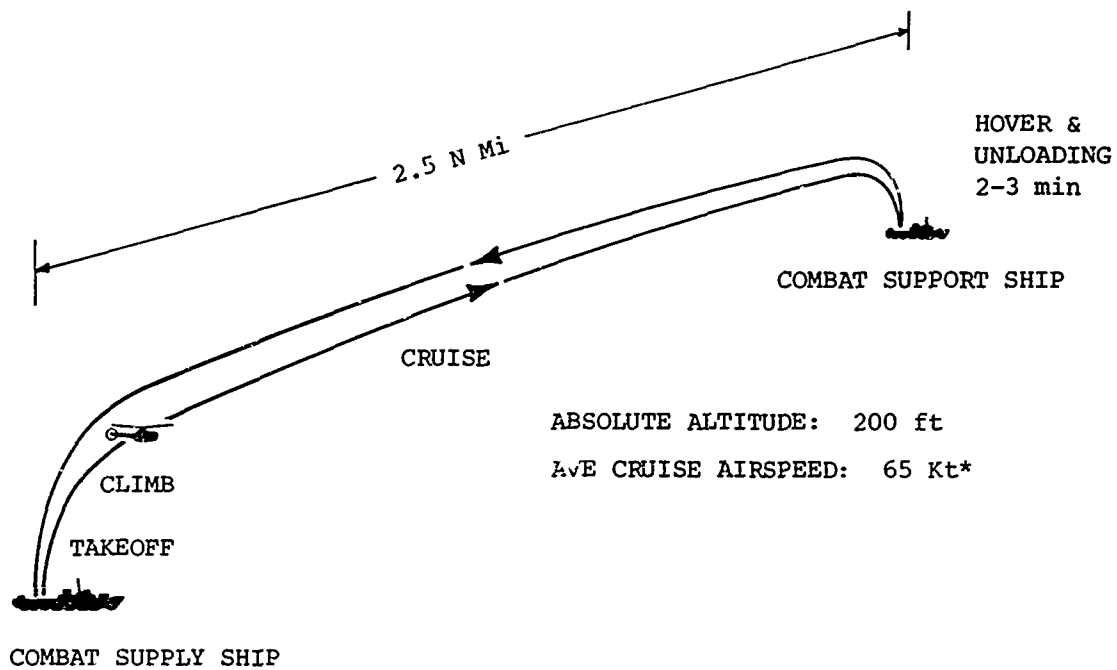
EACH MISSION:

Payload - 2 litter casualties and one rescue crewman, or four passengers, or 1250 lbs cargo

Mission Duration - 30 min to 2 1/2 hrs\*

\*Maximum endurance on station

FIGURE 7 SEARCH AND RESCUE MISSION PROFILE



**EACH MISSION:**

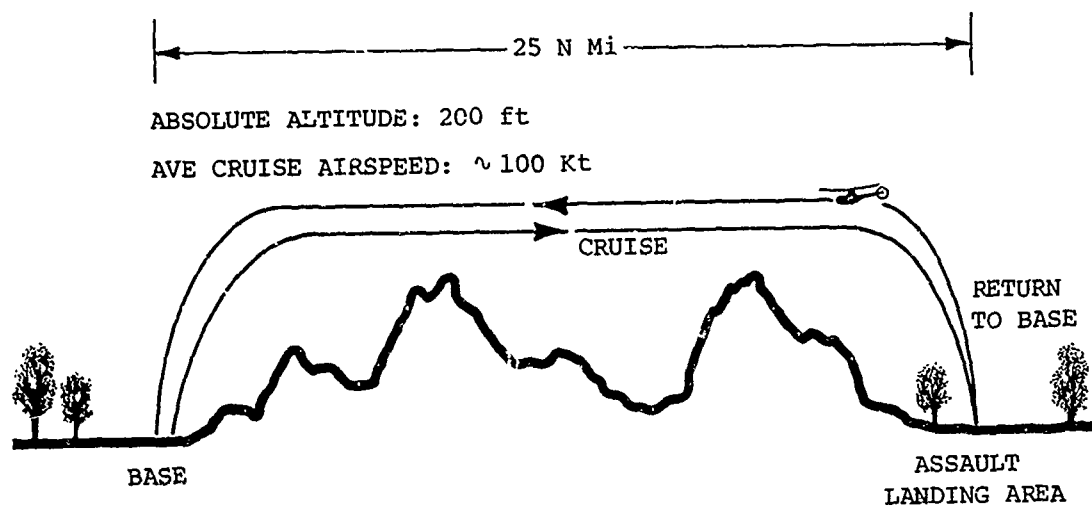
Payload - 4000 lbs max

Mission Duration - 1 to 2 hrs\*

\*Depends on weight of external payload

**FIGURE 8 VERTICAL REPLENISHMENT MISSION PROFILE**





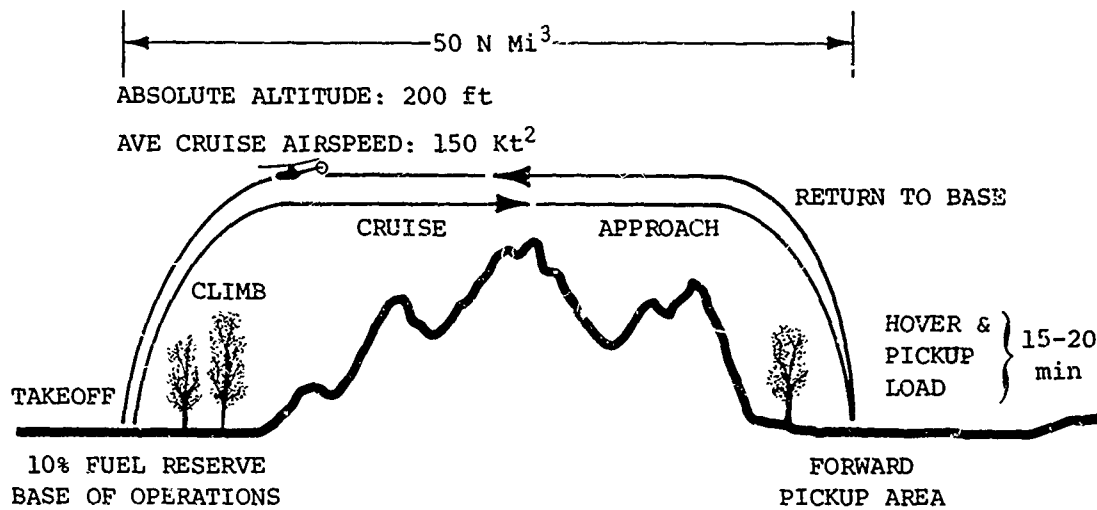
EACH MISSION:

Payload - 17 to 25 fully equipped troops (max - 4000lbs)

Mission Duration - up to 2 hrs\*

\*Depends upon distance to landing area and weather conditions

FIGURE 9 MEDIUM ASSAULT TROOP TRANSPORT MISSION PROFILE



EACH MISSION:

Payload - 8000 lbs<sup>1</sup> cargo

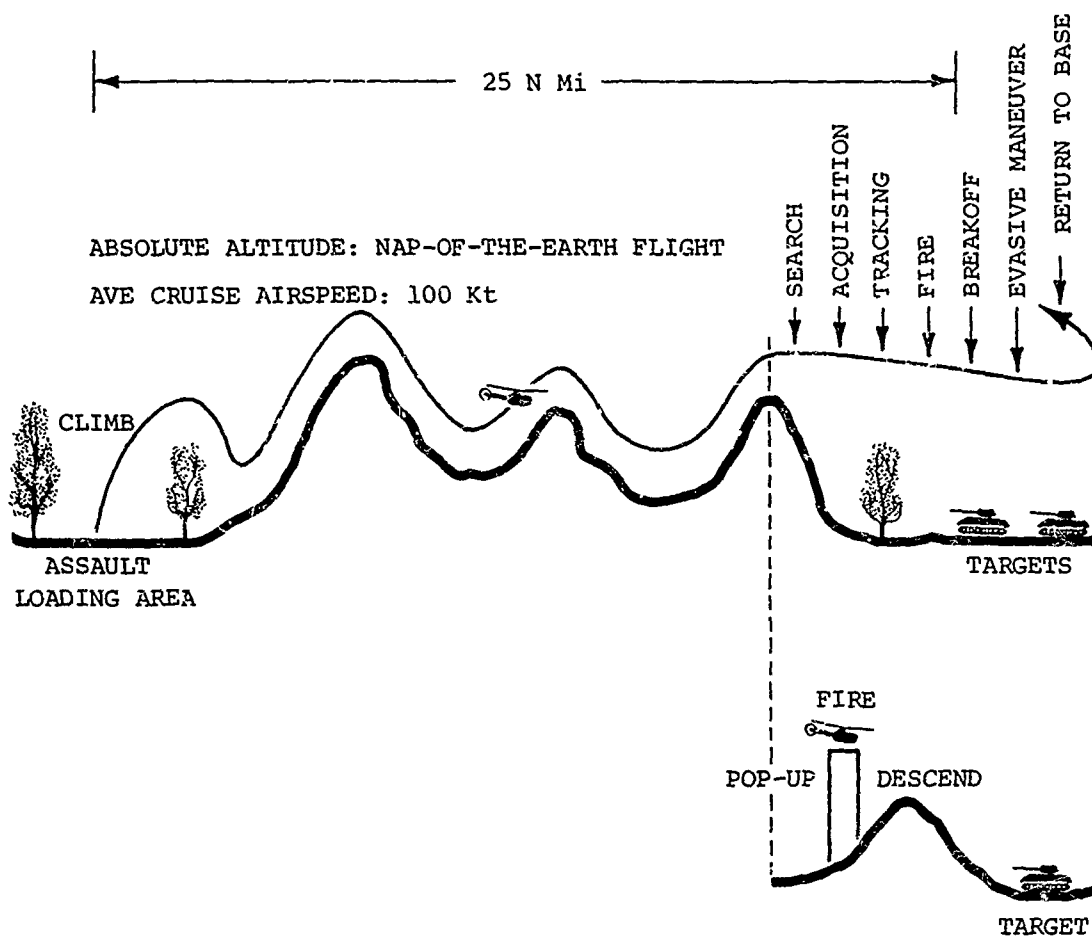
Mission Duration - radius of action 100 mi<sup>2</sup>

<sup>1</sup>May carry up to 20,000 lbs payload if carried externally

<sup>2</sup>Depends upon weight of load at pickup point

<sup>3</sup>Distance varies depending upon location of forward pickup area and weight of load to be returned

FIGURE 10 HEAVY TRANSPORT MISSION PROFILE



EACH MISSION:

Payload - observer or crew member - 200 lbs

Mission Duration - up to 3 hrs\*

\*Depends upon distance from targets and weather conditions

FIGURE 11 ASSAULT SUPPORT MISSION PROFILE

## SECTION 4

## CLASSIFICATION OF BEHAVIORS

Section 2 of this report provides an explanation and description of reported vibration characteristics found in contemporary helicopters. It relates these to selected studies on task performance and summarizes the findings, so that generalizations about methodology and results become more apparent. Section 3 provides a general description of Navy/Marine helicopters currently in use, their missions, special equipment, and operational requirements. In the present section we will examine the selected helicopter missions at a more detailed level in order to describe the tasks performed by the flight crewmen; and further, to identify and classify the perceptual and psychomotor behaviors involved therein. Then, by relating the vibration analysis results to these behaviors, we can identify potentially critical events, that is, those behaviors which are known or suspected to be susceptible to degradation under exposure to the operational helicopter vibration regime.

Additionally, because helicopters are being used in a broadening scope of activity, it is essential that we examine the operations, hardware and expected tasks associated with new missions. This will allow us to anticipate problem areas resulting from the effects of vibration on operator performance at an early stage. In this manner adverse effects can be minimized in initial design and development efforts, rather than through the experience of unsatisfactory performance, thereby obviating the need for expensive retrofits or extensive design modifications. Accordingly, we will describe and analyze the Advanced Aerial Fire Support System (AAFSS) mission concept, as well as other expected mission segments such as IFR station keeping and formation flying, and low visibility terrain following. Moreover, we will investigate the implications of developmental hardware such as the various helmet-mounted display devices and related tracking/pointing operations, the Integrated Helicopter Avionics System (IHAS) and other electronic cockpit displays.

As the trend in military helicopter operations continues toward more complex and demanding missions under instrument flight conditions and darkness operations, the prevalence of synthetic displays as sources for visual cues will approach that of present day high-performance fixed-wing aircraft. As a result, a whole new set of potential vibration-induced problems can be expected to emerge. For example, the use of Low Light Level Television (LLLTV) and Infra-red (IR) sensors for target detection

is even now imposing complex pattern recognition tasks upon crewmen. These often involve target detection in fields of high visual noise, low-brightness and low contrast. Crew performance on such tasks is almost certain to be adversely affected under vibration and other unfavorable environmental conditions.

Furthermore, tracking and pointing tasks which utilize mounted displays are dependent upon the operator's ability to track/point by means of head movements. The extent to which these tasks are vulnerable to helicopter vibration has not yet been determined. However, the degree of impairment may be substantial.

### General Description of the Helicopter Flight Task

The job of flying a helicopter is among the most complex perceptual-motor tasks found in practice. In response to a continually changing set of cues, the pilot must manipulate many controls in order to achieve a specific flight path or set of flight conditions. He accomplishes this by controlling the movement of the helicopter along and about the vehicle's three axes. Additionally, the pilot must monitor and time-share a number of displays, as well as shifting his attention frequently, attending both inside and outside of the cockpit. Further, he must anticipate and actively schedule his future activities. All of these tasks are carried out under essentially forced-pace conditions, since active monitoring, control and planning are essential to maintain a safe, stable state, and to complete a successful mission.

Helicopter flight control operations are accomplished by the pilot using four basic controls: the cyclic pitch control stick, which controls the left-right and fore-aft movement of the aircraft; the collective pitch lever, which controls the vertical direction of flight; the throttle, which controls engine RPM; and the anti-torque pedals, which control vehicle yaw. The cyclic pitch stick is controlled by the right hand and arm, the collective pitch lever and throttle are operated by the left hand and arm, and the pedals by the feet. The primary flight displays, as well as the displays and controls associated with engine and systems operation, are essentially the same as those commonly used in conventional fixed-wing aircraft.

The manner in which a typical helicopter flight should be reduced to its component maneuvers is somewhat arbitrary. However, in general, Navy/Marine Corps helicopter missions can be thought of in terms of some combination of the following eight basic maneuvers:

1. Ground Taxiing - maneuvering the aircraft along ground surface or flight deck using a combination of flight controls and toe brakes.
2. Vertical Takeoff to Hover - the helicopter is raised vertically from a spot on the ground to the manual hovering altitude with a minimum of lateral and fore/aft movement.
3. Hovering - the aircraft is maintained in nearly motionless flight over a reference point at a constant altitude and heading.
4. Hovering Turn - the aircraft is maintained at hover altitude and its heading is changed (to the right or left) while maintaining position over a reference point on the ground.
5. Straight and Level Flight - the aircraft is maintained in a stable state with constant heading, altitude and airspeed. (As with fixed wing aircraft, airspeed is determined by pitch attitude.)
6. Turns - the helicopter heading is changed (while climbing, descending, or in level flight) by banking the aircraft while maintaining longitudinal trim.
7. Normal Approach to a Hover - this maneuver is basically a power glide or descent. Angle and rate of descent, airspeed and heading are initially held constant as desired. Then forward airspeed and rate of descent are reduced to zero as the hover state is achieved.

8. Landing from Hover -

the aircraft is lowered vertically from a hover in a slow and gradual manner to the desired spot on the ground with a minimum of lateral and fore/aft movement or heading change.

Numerous variations are commonly introduced into nearly all of these maneuvers. Thus, a takeoff may be a rolling one, with continuing climb to altitude and with constant or varying forward speed and heading. Similarly, the descent may be continued directly into a landing by reducing altitude and altitude rate to zero simultaneously. Even emergency maneuvers, such as autorotation during actual or simulated power failures, involve variations of those maneuvers listed above.

As suggested by the mission profile and highlights data of Section 3, there are numerous other activities required of the pilot and copilot during a typical flight. They include monitoring cockpit displays, performing various radio voice communication and navigation tasks, visual search and tracking outside the cockpit, directing flight crew activities, monitoring flight progress, and planning the remainder of the flight.

As we indicated earlier, our basic reason for examining the helicopter flight task is to identify the human activities comprising it and to determine their susceptibility to the helicopter vibration environment. Therefore, it will be necessary to describe these task elements in a manner which enables us to interpret the available research results summarized in Section 2. In formulating such a behavior classification scheme we can profit from the results of earlier research efforts.

#### Other Flight Task Classification Schemes

A number of investigators have analyzed pilot flying performance in order to identify the tasks comprising it, and the skill and performance requirements involved. One such study by Fleishman and Ornstein (1960) is relevant in spite of the fact that it is focused on the fixed wing flight task. Measures of flying proficiency in 24 separate maneuvers were obtained on a sample of student pilots. The intercorrelations

among these maneuver performances were subjected to factor analytic study. The interrelationships were interpreted in terms of ability factors, most of which had been identified previously in laboratory studies of experimental perceptual-motor tasks. The factors were identified as:

Control Precision --	highly controlled muscular movements of arms, hands, legs, feet. (Fine Control Sensitivity).
Spatial Orientation -	judgments about one's location in three-dimensional space.
Multi-Limb Coordination -	coordinated use of multiple limbs, (Psychomotor Coordination).
Response Orientation -	the ability to make rapid response decisions under rapidly changing stimulus conditions.
Rate Control -	the ability to respond appropriately in relation to anticipation of velocity and rate changes.
Kinesthetic Discrimination	the ability to sense and utilize kinesthetic feedback (Postural Feedback).

The authors point out the limitations and hazards involved in the factor interpretation used. They recognize the fact that most maneuvers were factorially complex and that they might be interpretable in terms of common subtask operations or relationships. However, attempts at describing the ability factor at a more basic level seem to have produced unduly cumbersome and largely unfruitful results for their intended applications in the development of a practical and reliable in-flight performance measurement scheme. This set of ability factors does, however, provide a sound base to build on in developing our behavior classification scheme.

Two subsequent attempts at empirically deriving helicopter pilot performance measures (Zavala et al., 1965; Locke et al. 1965) also employed factor analysis to identify pilot maneuvers and individual tasks which are related in terms of performance requirements. In both of these studies pilot proficiency data were derived from Pilot Performance Description Records (PPDR) developed at Fort Rucker, Alabama. These PPDR's were obtained from evaluations made during certain standard flying maneuvers near the end of the Primary and Basic training phases. The



Primary phase evaluation involved 18 maneuvers, each of which included from 3 to 23 specific performance tasks or items. Similarly, the Basic phase evaluation was comprised of 16 maneuvers, each containing from 3 to 20 tasks (Locke et al., 1965).

The results of these studies indicate that performance scores tend to form into more molecular task factors rather than broader maneuver factors. Further, at least six such factors appeared to be common to the Primary and Basic training phases. These common task factors, and their associated abilities as interpreted by the investigators are listed below.

1. Engine RPM - involves dividing one's attention across several activities such as monitoring RPM indicator and other instruments, as well as cues from outside the aircraft; also involves the ability to make precise, controlled hand and wrist movements; requires ability to coordinate the hand-arm movements with pedal movements.
2. Airspeed - involves dividing one's attention between monitoring airspeed indicator while simultaneously performing other operations; also involves coordination of arm movements with visual cues from instruments; finally, accomplishing appropriate airspeed changes requires the ability to make appropriate rates of change in arm movements.
3. Line, End and Angle of Descent - the tasks here involve the achievement of a pre-determined approach path to a specific spot, thus fine coordination of fore and aft arm movements with external spatial judgments is required.
4. Rate of Closure - somewhat related to the Airspeed factor above, but requires the ability to maintain a constant apparent ground speed during landings (or in-flight rendezvous) by finely controlled arm movements, which are coordinated with external visual cues of motion.

5. Power Off Pitch Application - requires precise and well timed arm movements in attaining a soft landing; this timing involves the ability to judge distance and rate and to integrate them.
6. Drifts - sensing and preventing all drifts involves simultaneous movements of arm and feet; cues needed to make the appropriate movements are external visual cues and, to a lesser extent, kinesthetic cues.

These results reinforce the notion that complex tasks can be broken down into component parts without losing the relevance of those components in terms of the total task. And thus, in the assessment of helicopter pilot performance it is suggested that analysis of factors and associated central task elements is more meaningful than the analysis of maneuvers alone since identical task elements, and subsequently identical performance requirements can be observed in different maneuvers. This approach to analyzing the pilot's involvement in helicopter flight facilitates the identification of perceptual-motor factors since fewer task elements will be associated with a factor than were identified for maneuvers.

Utilizing the results described above as a point of departure, Ketchel and his colleagues (1969) formulated a set of ten central task elements and identified the perceptual-motor abilities associated with them. This scheme is reproduced in tabular form as Table 17. The perceptual-motor abilities which, for the most part, are widely used in the literature, were adopted by Ketchel et al. (1969) in part from a study by Parker et al 1965. These are reproduced from Ketchel's study as Table 17.

Ketchel and his colleagues used this behavior classification scheme to relate available research results on noise and vibration effects to the perceptual-motor factors present in commercial helicopter flight operations. For those ability factors where no research data was available the authors formulated judgments regarding the expected presence or absence of a degrading effect on performance. Their results indicate that significant degrading effects of vibration are reported, or can be expected for 13 of the 17 abilities listed in Table 18. A comparison of the abilities affected by vibration with their associated central task elements indicated that vibration would adversely affect the performance of all 10 central task elements involved in basic helicopter flying maneuvers.

TABLE 17

## PERCEPTUAL-MOTOR FACTORS RELATED TO CENTRAL TASK ELEMENTS

No	CENTRAL TASK ELEMENT	PERCEPTUAL-MOTOR ABILITY
1	Fore/aft cyclic control for: o airspeed attainment  o rate of change of speed o maintain ground speed constant	manual dexterity response orientation manual dexterity manual dexterity movement prediction perceptual speed
2	Combined fore/aft and lateral cyclic control	multi-limb coordination manual dexterity response orientation
3	Combined fore/aft cyclic control and throttle control	multi-limb coordination finger-wrist speed manual dexterity response orientation
4	Very fine cyclic control	manual dexterity finger-wrist speed speed of arm movement
5	Aft cyclic control	position estimation
6	Finely controlled swiftly executed cyclic control	arm-hand steadiness finger-wrist speed speed of arm movement reaction time manual dexterity
7	Fine control of collective pitch	speed of arm movement arm-hand steadiness position estimation
8	Throttle control	finger-wrist speed manual dexterity position estimation
9	Spatial-angular judgements	visual acuity distance-depth perception form-pattern perception motion perception time sharing
10	View flight area	distance-depth perception movement analysis movement prediction-tracking

TABLE 18

## PERCEPTUAL-MOTOR FACTORS

PERCEPTUAL FACTORS
<p>Visual acuity the ability to resolve visual detail.</p> <p>Perception of distance and depth the ability to distinguish relative differences in distance and to make absolute distance judgments.</p> <p>Perception of form and pattern the ability to identify or recognize shape, form, and pattern.</p> <p>Perception of motion the ability to detect relative motion.</p> <p>Movement analysis the ability to analyze velocity, acceleration, and higher derivative characteristics of target motion.</p> <p>Movement prediction tracking the ability to predict position through time.</p> <p>Perceptual speed the ability to make rapid comparisons of visual detail.</p> <p>Time sharing the ability to obtain and use information presented within more than a single display.</p>
MOTOR FACTORS
<p>Arm-hand steadiness the ability to make precise and steady arm-hand movements of the type which minimize strength or speed.</p> <p>Finger-wrist speed the ability to make rapid pendular and/or rotary wrist movements involving rapid repetitive jabbing movements in which accuracy is not critical. Does not depend on precise eye-hand coordination.</p> <p>Finger dexterity the ability to make rapid, controlled manipulative movements of small objects with the fingers.</p> <p>Manual dexterity the ability to make skillful controlled arm-hand manipulation of larger objects.</p> <p>Position estimation the ability to move a limb to a specified position when the position must be estimated rather than reproduced from an immediately experienced limb position.</p> <p>Response orientation the ability to choose and perform the proper movement or direction of movement from several alternatives.</p> <p>Speed of arm movement the ability to make discrete gross arm movements at maximum speed.</p> <p>Multi-limb coordination the ability to coordinate the movements of two hands, two feet, or a combination of hands and feet simultaneously.</p> <p>Reaction time speed with which a person can react to a stimulus.</p>

In our present study we will further expand and adapt Ketchel's taxonomy of task elements and associated basic behavior elements as necessary, to include the additional tasks and skills which comprise the various present Navy/Marine Corps helicopter missions. Our analysis will encompass the tasks of flight crewmen, as well as the pilots. Further, we will investigate future missions, hardware, and expected tasks with a similar modification objective in mind. Only through such a process can we arrive at a workable behavior classification scheme for assessing adequately the effects of vibration on helicopter flight crew performance.

### Flightcrew Tasks on Navy/Marine Corps Helicopter Missions

Section 3 delineates six basic helicopter missions and variations thereof in support of Navy and Marine Corps operations. For each of these missions, information is presented regarding operation requirements and responsibilities, critical events and segments, and special equipment available.

We will now examine the tasks of flight crewmen in the context of these mission environments and as performed with the equipment provided. Our intent here is not to compile an exhaustive listing of all crew activities that occur during representative flights, but instead, to identify those tasks which are comprised of behavioral elements likely to be susceptible to vibration effects as established by research findings discussed in Section 2.0. Thus, we will single out tasks which involve abilities or behaviors such as: visual acuity and dial reading, tracking and information processing, vigilance, target recognition, decision making and similar mental tasks.

In subsections following, we will successively examine each of the missions for relevant tasks; then we will consider the identified tasks collectively in an attempt to classify them into a manageable set of central task elements. Of the six Navy/Marine Corps helicopter mission types under consideration, the ASW mission is perhaps the most comprehensive and representative, in terms of the diversity of flight crew tasks required. Therefore, in relating vibration research results to mission-related tasks, we will utilize examples drawn largely from the ASW mission. Thereafter, in treating successive missions we discuss only those topics/tasks which are unique to that mission, or sufficiently different to merit special treatment.

## Anti-Submarine Warfare Mission Tasks

The ASW mission constitutes the Navy's primary requirement for helicopters. ASW helicopters comprise an integral part of the team acting as sensors for other units in a search and attack group. The helicopter's great asset in this capacity is its ability to extend the range of search, to detect, locate and attack a submarine, and to direct attack units (surface, sub-surface, and airborne) to the scene of action. Typically, the ASW mission consists of some combination and sequence of the following segments: proceed to designated area, hover, lower sonar and search for submarine, raise sonar, proceed to next area, hover and search, verify no submarine(s) present in assigned search area; or, detect submarine, localize, inform officer-in-tactical-command and attack or, maintain contact until arrival of attack unit, then participate in attack operations; finally, participate in attack effectiveness assessment.

As we have seen in the mission descriptive materials of Section 3, these operations must be carried out over extended time periods, during daylight and night-time operations from shore or shipboard bases, under adverse visibility conditions, at low altitudes, in close proximity to other operating units, with precise navigation, and with extensive tactical communications among participating units. A brief consideration of these conditions clearly contrasts the air crew task loading of this all-weather ASW mission with that of a daylight VFR point-to-point flight.

Let us re-trace the above mission segments to identify relevant central task elements. First, and perhaps most obvious, the pilots must be able to launch the aircraft, conduct the mission, and return to base with a bare minimum of reference to the outside world. This means that they must be enabled to navigate precisely for position fixing, they must have exact hovering capability and precise altitude holding ability, all with little or no external visual reference cues. This necessitates substitute sensors, data processors, and display devices with a corresponding shift in the nature of pilot visual tasks. Specifically, aircraft attitude and motion is controlled to a much greater extent by reference to such primary flight instruments as attitude indicator, altimeter, and airspeed and vertical speed indicators. Further, navigation and precision hover are also accomplished by reference to and interpretation of information presented on a variety of dials and horizontal situation displays. Fortunately, the pilots have been unburdened considerably in their tasks

by the addition of equipment such as hover indicators, hover trim control, automatic stabilization equipment and the coupler system. Nevertheless, the need remains initially to adjust and setup these devices, then to actively monitor and periodically re-adjust them as necessary. In addition to containing many basic motor capabilities, these tasks clearly involve visual acuity, information processing, tracking operations, and vigilance as important behavioral elements.

Certainly, performance of tasks containing these types of behavior elements is not confined to pilot functions alone. The sonar operators also have responsibilities requiring skill, concentration and coordination. When airborne on an ASW mission, detection and tracking of submarines are the primary responsibility of the sonar operator. However, his duties also must, of necessity, include certain rescue, look-out, troubleshooting, and minor maintenance duties applicable to the helicopter and associated equipment. (These latter duties, incidentally, are typical of non-pilot flight duties for all helicopter missions to be described in this section). Effective operation of the sonar equipment in the ASW mission environment includes the knowledge and skills required to activate, test, calibrate, adjust, and operate the system, as well as to log search results. These operations are comprised of many of the same behavioral elements as those identified above for pilot tasks. In paragraphs below these elements are discussed in terms of the vibration research results presented earlier, and their likely performance effects are identified.

#### Visual Acuity and Dial Reading

In Section 2 we saw a number of examples of laboratory research, which attest to the adverse effects of vibration on visual performance when this vibration falls within the dominant main rotor frequency range of 10 to 30 Hz. These results also indicate that degradation is likely to be more pronounced as a function of task difficulty, g-level, ambient lighting, contrast and workload.

Cockpit, crew station, and instrument panel lighting in military helicopters is reportedly marginal in many installations, due in part perhaps to the conflicting visual requirements inside and outside the aircraft; but whatever the reason(s), the visibility of many flight displays and other instrumentation and panel legending is marginal enough

that one might expect decrements in user performance. This expectation is at least partially confirmed by the results of one study involving the reading of printed numbers under low ambient light (0.1 ft L). In that situation reading errors increased by 21% under vibration conditions at 0.5 g acceleration, and ranging from 5 to 35 Hz. Other study results demonstrated clearly that a difficult dial reading task produces significantly greater errors, within the 0.3 to 2.4 g acceleration range, than an easy task.

These and other examples of research results presented in Table 3 on pages 14 - 20 suggest that helicopter flightcrew visual performance is likely to be degraded by vibration within the dominant main rotor frequency range of 10 to 30 Hz. Moreover, given the mission circumstances described earlier, it is reasonable to assume that general crewmember fatigue resulting from relatively long (up to 4 hours) exposure per mission, and the combined effects of temperature, noise, uncomfortable seats, or similar factors, will contribute to degraded visual performance on these ASW missions.

#### Tracking and Complex Mental Tasks

Just as vision is by far the most important sense modality in the pilot tasks described above, so is tracking a vital and all pervasive, central task element in the ASW helicopter mission. For example, achieving and maintaining a precision hover condition, either by reference to external cues or by using cockpit instrumentation comprises an important and representative tracking task. Similarly, flying to a specified point (such as target datum) by reference to the True Course and Distance indicator, or by using the Tactical Display Plotting Board, also represent complex tracking tasks. In fact, these more comprehensive operations themselves include a variety of simpler psychomotor tracking tasks such as achieving and maintaining desired heading, attitude and airspeed by reference to the instruments appropriate to each parameter. Suffice it to say that tracking is fundamental to pilot performance and, in the case of a helicopter ASW mission, much of it goes considerably beyond the simple psychomotor variety. With this in mind, we will consider briefly the research results from Section 2 dealing with tracking performance, and its implications for the ASW flight environment.



Summaries of the results of vibration studies on tracking performance point to the fact that such performance is severely affected in certain portions of the frequency range below 20 Hz, with acceleration in the 0.15 to 0.5 g region. It is also evident, however, that tracking performance is more likely to be adversely affected around the whole body resonance frequencies of 3-8 Hz. Both of these ranges span limitations specified in MIL-H-8501A, and they are above the 0.08 g Long Term Tolerance Curve for Military Aircraft (WADC). Other cited research results further affirm significant tracking performance decrements occurring at 0.2 g (5 Hz), 0.25 g (7 Hz), and 0.37 g (11 Hz).

Similar g-levels were used in an investigation of the independent and combined effects of multiple axis vibration. Results indicated differing effects of y-axis vibration at the low frequencies studied, with certain combinations of frequencies and axes being more detrimental. Thus, in general, research evidence indicates that tracking performance decrements can be expected under exposure to the vibration frequencies and accelerations characteristic of rotary wing aircraft. Moreover, accurate assessment of the extent of such vibration effects must include the combined effects of several frequencies, amplitudes and axes, as well as exposure duration.

There can be little doubt that pilots, as well as sonarmen are confronted with complex and demanding tasks for extended time periods during a typical ASW mission. The complexity of the pilots' tasks in the ASW helicopter mission is widely recognized. However, although the safety and survival of the aircraft and crew are not as dramatically at stake, the sonarman has an exceptionally demanding and difficult job. This fact is convincingly stated in the NATOPS Flight Manual for the SH-3A ASW helicopter:

There is no aspect of the airborne sonar operator's job more fundamental to the success of the ASW mission than the proper classification of an unidentified contact encountered while echo-ranging. Few tasks performed in the Navy call for as much skill in the proper use of equipment or more logical analysis by trained evaluators than that of determining the nature of a target from the cues provided by the audio and video displays of sonar."

Most contacts reveal a great deal about themselves to those who know what to look for. Only an individual with highly trained eyes and ears will see and hear the important details that reveal the nature of an unidentified sonar contact."

"...Furthermore, the skilled operator can manipulate his equipment controls in such a way as to maximize the information obtainable about the target."

Research results regarding the effects of vibration on complex mental tasks are included in the tables and discussion presented in Section 2 of this report. Performance decrements were cited in each of three tasks: target identification, warning light monitoring, and probability monitoring. Moreover, the evidence also indicates that one of the problems associated with the evaluation of complex task experiments is that of priority assignment. That is, in the case of studies which require time-sharing across several tasks, some subjects attend more closely to tracking, while others concentrate on minimizing response time to warning lights. Thus, it may well be that measurable performance decrements in an operational setting are occasionally not found for the most difficult among several tasks simply because that task is attended preeminently, and at the expense of others.

#### Decimal Input Device Operation

Accurate navigation for position determination, as well as tactical uses, is an important function in the ASW helicopter mission. As indicated in Section 3, an extensive variety of special equipment is provided to assist the crew in performing this essential function. These operations are assigned to the copilot. Very close attention and precise control of input of the desired settings is mandatory to gain the full and accurate use of the navigation equipment. Operation of this equipment involves the use of toggle switches, continuous rotary knobs, pushbutton and other conventional controls and displays.

As indicated earlier, the sonar operators' tasks likewise involve a heavy use of controls of this type to make timely and precise adjustments and inputs.

Laboratory research results cited in Section 2 attest to the fact that these kinds of motor tasks are indeed susceptible to degradation under vibration in the main rotor frequency range of helicopters. Input devices studied included: pushbuttons, toggles, rotary switches and thumb-wheels. Not only was performance generally degraded, but no single one of the controls was best for speed, accuracy, and user preference.

### Search and Rescue Mission Tasks

As the mission label suggests, the primary task of the Search and Rescue (SAR) helicopter mission is to serve as plane guard and rescue for carrier and other surface ship operations. Long range is generally not required, since individual flights are generally conducted in the immediate vicinity of the parent carrier. However, the capability for longer range missions is required in order to recover downed pilots or other survivors discovered at distances from the mother ship (or parent air station). Additionally, in some mission variations, relatively long times on station (up to approximately 4 hours) may be required to conduct a search or to retain contact while aid is en route.

The SAR mission could conceivably include some combination of the following events: take station in the air during aircraft launching and landing operations; recover personnel from downed aircraft and return to carrier; serve as a retriever of personnel lost overboard from ships; conduct close-in search from shore bases and recover personnel and critical items; perform short range reconnaissance, courier service, and personnel transfer missions.

As indicated by the mission data appearing in the tables of Section 3, the SAR helicopter mission necessitates a capability for hovering and retrieving personnel and equipment by hoist. It is capable of operating in all climates and from floating or shore bases, as required. Precise navigation equipment is installed, and in some cases, special radio direction finding equipment may be provided for locating survivors down at sea. As with the ASW mission, the SAR mission is conducted as necessary on a 24-hour, all-weather basis.

Clearly, many parallels exist in the operations comprising the SAR and ASW helicopter missions. Precision maneuvers, hover at low altitudes, and performance of navigation-related tasks,

are but a few immediately apparent examples. And, in both missions, these operations may be carried out under adverse visibility conditions, and for prolonged time periods. Similarities are also evident in the needs for a high degree of crew coordination, and in the requirements for extensive radio voice communications with other participating units.

Because of these and other similarities in mission task elements, many of the areas of performance decrement expected in the ASW helicopter mission environment are also applicable to the SAR mission. But additionally, there are certain aspects of the pilots' and the rescue crewman's tasks which are sufficiently different and also likely to be vibration susceptible, which merit discussion.

From the SAR mission description tables of Section 3 it can be seen that the rescue pattern is the maneuver which distinguishes the SAR mission from others. Carrying out this operation under night and low visibility conditions requires a great deal of skill and concentration, as well as close coordination among all crewmen involved. In this operation the pilot must achieve a specified flight pattern by precise control of attitude, airspeed, altitude, rate of descent, and path over the water. And, this must be done almost exclusively by reference to his cockpit instruments, and supplemented by verbal guidance cues from the copilot and rescue crewman. The copilot provides supplementary guidance information to the pilot by reference to the tactical display plotting board, and later in the approach, uses previously dropped electric marking lights as a reference for approaching the target. Although the rescue pattern is nominally flown with considerable assistance from on-board guidance and stabilization equipment, it is essential that both pilots monitor the progress of the various maneuver segments throughout the approach and be prepared to disengage altitude control and take-over manually if automatic control does not perform reliably. Once in the immediate target area and hovering generally over the survivor, the pilots must rely more on verbal guidance from the rescue crewman in order to achieve and maintain a precise position over the survivor.

Thus, although different from the ASW sonar dipping hover maneuver, the rescue pattern maneuver imposes similar demands upon the crewmen. Use of cockpit instrumentation, flight controls, and navigation equipment in achieving and maintaining the desired flight pattern include requirements for visual acuity and dial reading, tracking and complex mental tasks, and a high degree of concentration and vigilance. The shorter duration of the rescue pattern, and the SAR mission in general,

may result in less degradation of performance as a result of vibration exposure. The rescue crewman's tasks are characterized by heavier motor performance elements and require greater physical exertion than the sonarman's more sedentary activities, but the rescue crewman's performance can be expected to suffer less from the helicopter vibration environment.

#### Vertical Replenishment and Utility Mission Tasks

Resupplying ships at sea with ammunition, stores and supplies from other floating bases constitutes the primary operation of this mission. Resupplying ships in this manner expedites replenishment and preserves a measure of safety to vessels at sea in that transfer can be accomplished without reducing ship maneuverability. Transfer is effected either by landing on a ship's deck and off-loading, or by conveying the materials externally and lowering them onto the ship's deck. Thus, cargo moving equipment and containers, and vertical hoist capability are provided. Typically, the replenishment mission is characterized by multiple round trips of relatively short distance, with multiple hover/landing segments included. Although aircraft flight instrumentation and navigation equipment capabilities are not as great as the ASW and SAR missions, operations in marginal weather conditions are not unlikely.

From an analysis of the mission descriptive data of Section 3 it becomes apparent that the distinguishing characteristics of the Vertical Replenishment mission, from a task performance standpoint, are the hover/landing operation requirements with maneuvering ships. Under some conditions these operations must be carried out with great precision, under poor visibility conditions, and with highly restricted maneuvering room.

In this situation the complexities of the ASW or SAR type of hover maneuver are further increased by the fact that the hover reference point (the ship) is moving, and may change direction or speed of movement. Similarly, if a landing is required, the available deck area is frequently less and the hazards of nearby obstructions (ship superstructure) may be greater than the mother ship setting.

In spite of some of the differences in mission circumstances cited above, it is our contention, however, that the nature of the tasks and the resultant performance demands on the crew are essentially quite similar to those imposed by the SAR

mission. On the other hand, the replenishment mission is typically of shorter duration than the others cited; however, it involves frequent hover situations and multiple takeoffs and landings, with relatively high crew task loadings relative to the loiter portion of the SAR mission.

The net results of our examination of the vertical replenishment mission is the conclusion that many of its task demands are similar to the missions examined earlier. However, the generally shorter duration of the mission, the generally better visibility conditions expected, and the largely motor performance requirements characteristic of the crew chiefs' tasks contribute to making the crew of the Vertical Replenishment mission generally less susceptible to degraded performance as a result of exposure to the vibration environment than the earlier described missions.

#### Medium Assault Troop Transport Mission Tasks

As its title suggests, the primary purpose of this mission is to transport personnel and cargo during ship-to-shore operations and within an objective area. An additional important operation is to conduct evacuation operations of casualties from battlefield to rear areas or to a ship. These operations can greatly increase ship to beachhead speeds. They make it possible to take advantage of vulnerabilities in any particular defensive disposition, and the accomplishment of this is not dependent on beach conditions. Around the clock, all-weather operating capability is essential, thus flight instrumentation, communications, and navigation equipment comparable to that on earlier described missions is provided.

Reference to the mission descriptive data of Section 3 suggests a relatively straightforward array of flightcrew tasks. The all-weather requirement of this mission, as with others discussed previously, necessitates complete reliance by the pilot on the cockpit flight instruments under certain conditions. The mission also burdens the copilot with the duties of operating/monitoring the navigation equipment, and monitoring tasks similar to those described in the ASW and SAR missions. Additionally, the requirement to fly over unfamiliar terrain at low altitudes and under reduced visibility conditions with accurate position determination imposes a high task loading on the crew. In this situation they must

time-share among numerous within-cockpit and extra-cockpit visual cues for attitude control, terrain clearance, and position indications. The copilot must monitor flight progress as indicated on the map plotter display and relate it to recognizable terrain features and check points, then update the navigation equipment, and generally assist the pilot in directing the flight to designated objective areas.

Clearly, these tasks are comprised of many of the same behavioral elements identified in previously described missions. And, insofar as some of the task elements such as visual acuity, complex tracking, target identification, information processing and other complex mental tasks play a significant role in overall crew performance, that performance can be expected to suffer under exposure to the helicopter vibration environment. However, as we have also indicated earlier the extent of performance degradation is influenced by a number of additional factors. Among them is the complexity of the various task elements, the sequence in which they occur, the task loading which results, and the duration of that loading. Applying these considerations to the Medium Assault Troop Transport mission tasks we must conclude that some crew performance degradation can be expected to occur, particularly if multiple sorties are flown under adverse conditions. However, such degradation should be relatively small compared to the ASW and SAR helicopter missions.

#### Heavy Transport Mission Tasks

The Heavy Transport mission is intended for (1) transporting cargo and personnel during ship-to-shore movement and within an objective area; and (2) conducting evacuation operations of casualties from a combat zone to a rear area or to a ship in all-weather conditions. Cargo and personnel are delivered to a specified area by helo-lift or by external carry, and wounded are evacuated either in the cabin, or by litter carry in situations wherein landing cannot be effected. As with all the missions discussed in this section, the Heavy Transport mission requires flight instrumentation, communications, and navigation equipment for instrument flight. It must be able to operate from floating bases, and should also have an amphibious capability.

In many respects this mission bears a strong resemblance to the Medium Assault Troop Transport Mission discussed earlier in this section, the major difference between the two being

size and weight carrying capacity of the aircraft used. There is little evidence of significant differences in the operating conditions and environments, in the equipment to be utilized and in the mission durations.

From a crew task standpoint the tasks are also quite similar. Those differences which do exist stem largely from such factors as the following: the heavier aircraft is likely to require greater control operating forces, it is likely to respond slower and more sluggishly to control movements and as a result is less maneuverable. Additionally, longer periods at hover are likely in the Heavy Transport mission than in the Medium Assault Troop Transport mission.

Based on our analysis of the research results in Section 2 and the mission data of Section 3, we must conclude the following: in a typical operating environment and with adverse weather/visibility conditions measureable decrements in pilot performance in the Heavy Transport mission can be expected following extended exposure to the helicopter vibration environment. Moreover, we would predict that this decrement will be greater than that expected from equal flight durations in the Medium Assault Troop Transport mission.

#### Assault Support (Fire Control) Mission Tasks

This mission involves low altitude, nap-of-the-earth flying in enemy territory for the purpose of detecting and firing upon enemy troops, equipment and installations. The concept and intent are to take maximum advantage of concealment from enemy observation and fire afforded by terrain variations. The aircraft utilizes pop-up tactics to acquire and fire upon the enemy, then drops down again behind cover or concealment.

Flight instrumentation provided is adequate for marginal weather and limited night operations. Radio aids for navigation, as well as a self-contained navigation system are also provided. A communications capability permits tactical cooperation with ground troops, ships, and other air support forces.

Air crew tasks on this mission are significantly different in many respects from those discussed in prior missions. Although the mission capability includes operation under marginal visibility conditions, and hence requires the pilot



to fly at least partially on instruments at times, the mission comprises seat-of-the-pants flying to a considerably greater extent than those previously cited. Moreover, the very low altitude, nap-of-the-earth flying represents a special kind of complex tracking task requiring a high degree of skill in many perceptual-motor factors. Included are visual acuity; distance and form perception; motion perception, analysis and prediction; multi-limb coordination; response orientation; reaction time; and others.

Further tasks required of both pilot and aerial gunner/observer involve observing areas of suspected enemy activity, detecting and identifying targets, and achieving an optimum pop-up position to fire effectively on selected targets. These tasks too, involve heavy reliance on factors such as visual acuity, target recognition and tracking, and other of the previously mentioned skills. Finally, since the guns are fixed relative to the airframe, the pilot must maneuver and point the aircraft to achieve and maintain a required firing position. Still another variation in tracking behavior is represented by the monitoring of tracer bullets to determine firing effectiveness, and adjusting vehicle attitude/position accordingly to retain or regain an on-target firing situation.

It should be evident from the above discussion that crew performance in this type of Fire Control mission involves a heavy reliance on visual cues obtained from the external world in order to perform complex tracking tasks in a highly dynamic and fast-moving sequence. Furthermore, the task loading and concentration required of both crewmen for extended periods (up to 3 hours) is intense. Thus, on the basis of research results discussed earlier as applied to this situation, we would expect measureable crew performance decrements following exposure to this helicopter mission vibration environment. Moreover, the maneuvering/tracking aspects of the pilots tasks are expected to suffer more than the search, detection identification and visual tracking tasks of the aerial gunner/observer. However, insofar as the observer is further burdened with the tasks of operating and monitoring the self-contained navigation system during such flights, that performance can be expected to suffer more noticeably from extended exposure to the helicopter vibration environment.

In the subsections above we have examined representative presentday Navy/Marine Corps helicopter missions from the standpoint of flight crew tasks to be performed and the circumstances under which they are performed. We have then attempted to relate this mission-oriented information with laboratory study

results on task performance under vibration conditions in order to predict vibration effects in the operational setting. We have concluded that, in varying degrees, nearly all pilot flight tasks are likely to be adversely affected as a result of exposure for nominal mission durations.

In succeeding paragraphs we will discuss briefly some of the expected further missions, more sophisticated hardware, and resultant complex tasks which will confront helicopter flight crewmen. Again, our concern will focus on the behavioral elements and perceptual factors comprising these new tasks in order to anticipate their susceptibility to degraded performance in the expected helicopter mission environment.

#### New Developments in Missions, Hardware and Crew Tasks

From the information in Section 3 we have seen that, in military tactical situations, the helicopter has particularly demonstrated its ability to perform a broad range of missions under adverse environmental conditions. As a result, the helicopter has become an important part of the present Navy/Marine Corps operations and in their future plans. However, it is widely recognized by operational commanders and mission planners alike, that one of the major limitations to more widespread and diverse application of rotary wing vehicles has been the difficulties of helicopter instrument navigation and flight control with existing instruments. The various missions, associated equipment, and resultant tasks discussed in earlier sections suggest that considerable progress has been made in the military toward achieving all-weather capability for some applications.

Nevertheless, many of the potential future applications would require that large numbers of helicopters fly in coordinated formations to selected sites, launch attacks or unload their cargo and/or personnel, and then evacuate the area in a minimum of time. Under clear visibility conditions, helicopter formations have repeatedly performed this mission with a high degree of efficiency. But marginal or adverse weather conditions prohibit this mission because of the limited capabilities of present day avionics systems.

Additionally, essential aspects of the above hypothetical future missions are target detection, identification, acquisition, and weapon sighting, when such targets are not visible to the naked eye. These types of functions impose a

whole host of requirements for new developments or applications in airborne sensors and displays. And with these developments come a wide variety of complex crew tasks. In following subsections we will briefly treat these missions, equipment, and tasks and make some predictions regarding the vulnerability of the tasks to helicopter vibration effects.

#### Advanced Aerial Fire Support System (AAFSS) Mission

The AAFSS mission is intended to provide armed escort for other support helicopters and to serve as a ground attack aircraft. It must have an all-weather capability, terrain-following radar and other sophisticated navigation and fire control aids. It must be provided with turret-mounted guns, rockets and other ordnance. The pilot must be provided with sufficient displays (forward view and plan view) to carry out adequately his task of low level flight to and from the target area under adverse visibility conditions.

Clearly, the mission has many of the characteristics of the previously described Assault Support Mission, wherein both crew members are required to perform complex tracking tasks in a highly dynamic and fast-moving sequence for extended periods. In that mission, however, those tasks are performed largely by reference to external visual cues; whereas in the AAFSS mission the required tasks will be performed in many cases by using synthetically generated displays driven by a variety of sophisticated sensor systems.

The implications of this task environment for flight crew performance under vibration conditions should be fairly apparent. We have a situation requiring visual acuity, pattern recognition, complex tracking, time-sharing, response orientation, and many more perceptual-motor abilities, most of which are related in some way to the various cockpit display systems. Accordingly, we predict with some measure of confidence that the anticipated helicopter vibration will degrade crew performance significantly in the AAFSS mission.

#### Integrated Display Systems

We have seen from the AAFSS mission, as well as some of the other previously described missions, that the performance

of advanced helicopter flight tasks under instrument conditions requires the development of more sophisticated, but perceptually simpler integrated display systems. Several developmental programs sponsored by the military services are currently under way to provide such a new generation of avionics equipment for a variety of mission applications. One of the early, and perhaps best known, of these programs is the Integrated Helicopter Avionics System (IHAS). The objective of this effort is to develop an integrated system which will perform the airborne functions of navigation, flight control, station keeping, terrain following, terrain avoidance, and monitoring equipment status.

Thus, by displaying on a Vertical Situation Display (VSD) a synthesized picture of real world elements as normally seen under VFR conditions, and integrated instrument elements such as actual and command altitude, airspeed, and pitch information, vertical orientation can be attained. Similarly, a Horizontal Situation Display (HSD) can depict aircraft present position, heading, command course, fuel/range information, and radar map information in plan view form in front of an aircraft symbol, all superimposed on a map presentation having selectable scales.

In addition to radar data, the HSD is also likely to be used to present displays of other information such as infrared (IR) and/or TV. These types of sensors thus will yield plan view data for purposes of updating the navigation system or for detecting, identifying and locating targets.

Still another application for this type of display is a development effort which is focused on a Formation Flight System (FFS). Typically, such a system may consist of a collection of sensors, data processing equipment, displays and controls which determine the identity and position in space of the formation aircraft. It displays this information to the pilots of various aircraft so as to permit maintenance of the formation geometry through various flight maneuvers under instrument flight conditions, and by manual as well as automatic flight control.

The use of such pictorial displays provides a more direct link for tying the sensor data to the real world of things and obstacles. Obviously, the value of such a form of presentation is directly limited by the crewman's ability to recognize checkpoints and targets; therefore, this problem deserves utmost attention in determining its suitability for the operational helicopter environment.

The addition of these types of integrated display systems, improved navigational equipment, automatic flight control systems, terrain avoidance and other sensor systems will greatly increase the scope of operational capabilities of future helicopters, but it will also result in additional stresses and task loadings on the flight crewmen. Moreover, based on our review of the laboratory research results presented in Section 2 and our analyses earlier in this section, we must conclude that these forthcoming task burdens are of the type which will be susceptible to performance decrement under exposure to the expected vibration regime.

### Helmet Mounted Display Devices

One outgrowth of the integrated display system development efforts has been a growing interest in mounting displays on a pilots' helmet as a simple means of presenting real-time radar, IR or TV imagery data to helicopter crewmen.

A helmet display system might also serve as an integral part of the helicopter fire control system, particularly if it is combined with a helmet-mounted sight. A sight of this type has been planned for use by AAFSS crewmembers and is currently in production at Honeywell.

A helmet-mounted sight and display combination, utilizing a head-tracking technique, could enable a helicopter pilot or gunner/observer, to direct conventional turret mounted machine guns or more sophisticated sensor-guided weapons, by the movement of his head. In the latter case the weapon's seeker would be slaved to whatever the weapon's sensor sees, would be projected before the crewman's eye, superimposed over his view of the real world as he carries out his visual search for targets. The impact of this on other visual tasks and performance requirements has not yet been determined.

Several other variations in these basic uses of the helmet-mounted display concept are under development by a number of manufacturers. Some design approaches use a single cathode ray tube and others use two; some use a single eyepiece, with one eye unobscured, and others occlude both eyes. Similarly, a number of head-tracking concepts for use with the helmet displays are being developed. These include mechanical, optical, and electronic techniques.

Much laboratory research and operational evaluation is necessary before conclusions can be drawn about such diverse considerations as the value of optimal display usage or the sighting/pointing applications of helmet-mounted displays. Anecdotal evidence indicates surprisingly favorable initial reactions from a limited number of pilots who have used helmet-mounted displays.

On a field visit to the Honeywell facility in Minneapolis, the authors received a briefing on the Honeywell Helmet Sight System, and wore an experimental version of it while performing a head-tracking task in a laboratory setting. Bearing in mind that it was a familiarization experience, our first impression was one of cautious optimism. After several brief tracking runs on a moderately evasive target, we found the dynamics of the head-tracking task surprisingly natural and easy to adapt to. On the other hand, the task setting was nearly ideal and the task was greatly simplified in that a relatively bright reticle was provided, with which to track a small, bright target. The task was performed in an isolated booth with an almost uniformly dark visual field. These conditions are in no way representative of a real world situation, and were not intended to be. Nevertheless, the first-hand experience of performing the tracking task by means of head movements proved to be very convincing. Novice performance and confidence seems to improve markedly after but a few trials, and the general feeling among those who tried it is that it has excellent potential for a number of applications.

The developers, too, are enthusiastic about the potential applications of the helmet-mounted display concept. However, they urge caution, extensive engineering planning, and considerably more basic research on the human performance aspects of the device, before launching into the many appealing avenues of operational applications.

The recent technical advances which are making possible the helmet-mounted display concept coincide with the growing military need described earlier to display a multiplicity of airborne sensors in already crowded helicopter cockpits. Thus, this development is an extremely welcome and timely one.

From the standpoint of flight crew performance in the helicopter vibration environment, the prospects also seem quite encouraging. First, and perhaps most important from the standpoint of vibration attenuation, the helmet-mounted display will have no "hard" attachments to the airframe. Thus, the amount of vibration induced from the airframe is

minimized since attenuation takes place in the seat, the cushion and the crewman's body. Secondly, although main rotor vibration in most helicopters does span the resonant frequency of the head (20-35 Hz), it is not expected to constitute a problem since it lies in a region where effects tend to be less severe, and more easily attenuated. Therefore, vibration of the head/helmet/display complex, taken either collectively or individually, should not be of a magnitude which leads to performance problems. In our opinion, a problem of some significance and perhaps of major importance, is likely to result from the large amplitude low frequency buffeting characteristic of flight in turbulent air. This condition would seem much more likely to produce degraded head-tracking performance than the expected helicopter vibration environment. Obviously, extensive experimentation and operational testing is the only avenue to determining the validity of our predictions.

## Overview

In this section we have examined the tasks of Navy/Marine Corps helicopter flight crewmen in order (1) to identify and classify the behavioral elements and skills comprising their activities; (2) to relate the results of our vibration analysis to flight crew tasks; and (3) to identify crew task situations which are likely to be susceptible to degradation as a result of exposure to helicopter vibrations.

The importance of task elements such as visual acuity and dial reading, tracking and complex mental tasks, and various control operating tasks in all-weather military helicopter missions was recognized. Moreover, the reported influence of vibration on the performance of these tasks was considered and then some conclusions were formulated regarding expected crew performance degradation in each of six representative military missions. Similar predictions were developed regarding future missions, equipment and crew tasks.

Our analysis of helicopter missions and crewmember tasks indicates that a rank ordering of mission in terms of their susceptibility to the effects of vibration would be both tentative and tenuous. A ranking of mission difficulty that seems suitable for pilot tasks requires restructuring when non-pilot crewmembers are considered. Further, critical events, available equipment, and other contingencies can readily shift the rank

ordered difficulty level of a particular mission whether pilot, non-pilot, or all tasks are considered. Nevertheless, in general we can rank ASW, SAR, and Assault Support (AAFSS future mission) as the three missions which are potentially the most demanding on crewmembers, and the most susceptible to the effects of vibration and other adverse conditions. Less vulnerable missions include Vertical Replenishment, Heavy Transport, and Medium Assault Transport. Of all missions, however, ASW consistently ranks highest as the most demanding and most susceptible.

Turning to future missions, hardware, and expected crew tasks, we have seen that a wide variety of synthetic displays and sensors are likely to be used for the presentation of flight, navigation, and weapon delivery information. These developments will greatly increase the scope of operational capabilities of future helicopters, but will impose additional stresses and task loadings on the flight crewmen. Specifically, displays presenting sensor information such as radar, IR, and LLLTV, wherein complex pattern recognition tasks are involved, are likely to be adversely affected by the vibration regime. To a lesser extent, crew performance in the use of synthetically generated displays with standardized symbology is also likely to be degraded under helicopter vibration conditions.

A promising approach to the presentation of information in helicopters is manifest in recent developments of helmet mounted displays. Here, the effects of vibration may or may not be of prime importance. Additional development work and concept testing is required before the effects of vibration or other environmental factors can be determined for these devices.



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In preceding sections we have discussed the impact of the helicopter environment on the crew's ability to perform assigned tasks. However, we are also concerned with those hardware items and aspects of equipment design which are likely to influence both the characteristics of vibration which are generated and one's subjective assessment of them. For example, seat design and the development of vibration isolation techniques are likely to have an impact on the magnitude of vibration eventually experienced by flight crewmen. These, and other topics are given individual treatment in the present section.

#### In-Flight Tracking of Rotor Blades

Pilot-operated in-flight tracking of rotor blades was pioneered by Kaman Aircraft engineers in the late 1950's (Coleman, 1958). The adjustment device provided the pilot with a means to bring his rotor blades into track under a variety of flight conditions. It saved time and manpower, allowing tracking adjustments to be made away from the home base, and eliminating the need for groundcrewmembers using track-by-flag methods. More recently, Kaman has developed an automatic in-flight blade tracking system, and has installed it on the UH-2 Seasprite as production equipment.

The NATOPS Flight Manual for the UH-2C describes two types of out-of-track condition which can occur. The first is caused by one blade being out of track with respect to its 180-degree counterpart; the second by two opposing blades (of a 4-blade system) being out of track with respect to their two 90-degree counterparts. The first condition can cause vertical vibration at a frequency of one cycle-per-rotor revolution (one-per-rev or 1/rev), which is approximately 4.5 Hz.

Kaman's blade tracking system continually detects and corrects the one-per-rev type of out-of-track condition whenever it occurs. This is accomplished by use of a vibration-sensing device which detects vertical vibrations and produces proportional electrical signals for additional processing.

The system is said to perform effectively in minimizing the troublesome 1/rev vibration which occurs in the low

frequency region. It is particularly well suited for 2 and 4-blade helicopter applications.

The use of such devices by other airframe manufacturers should be encouraged. The lack of in-flight blade tracking equipment is often mentioned by pilots as a deficiency which requires attention (Ketchel et al., 1969).

### Vibration Isolation and Absorption Techniques

Section 2 data indicate that helicopter dominant frequencies occur in the 10 to 30 Hz region and that harmonics of progressively milder intensity occur at higher frequencies. In addition, a 1/rev spike is found below 10 Hz on the low frequency side of the n/rev peak. However, its effects are said to be minimized by proper blade tracking and, if so, tend to be negligible.

These conditions produce stable and predictable vibration frequency patterns during the majority of the time that a helicopter is airborne. Therefore, ideally, the dominant frequency can be determined and acceleration amplitudes can be controlled within acceptable limits by virtue of a properly designed vibration isolation device. By this we mean one tuned or notched to provide maximum isolation at the peak frequency value.

Unfortunately, things are not quite so simple. Variability is introduced into an otherwise stable frequency pattern by the random effects of wind gusts, severe maneuver loads, and changes in rotor speed. The impact that these are likely to have on human performance or biomedical status depends on the following:

- o the transitory nature of the condition, i.e., the brevity of it
- o its severity
- o its frequency of occurrence
- o the duration of exposure to those conditions which occur frequently
- o the difficulty of the performance task
- o individual susceptibility

In general, brief transitory conditions are tolerable unless they are quite harsh or occur frequently over a relatively long time period.

Consideration will be given to RPM drift later on when the merits of two of the leading techniques for vibration isolation, electrohydraulic systems and the Dynamic Anti-resonant Vibration Isolator (DAVI), are compared. For the present, however, we turn to a discussion of the more familiar vibration control methods.

Ruzicka (1968) distinguishes between active and passive vibration isolation categories on the basis of external power requirements. He provides the following examples in each category.

"The essential features of a passive isolator are resilient load-supporting means (stiffness) and energy dissipating means (damping). Typical passive isolators employ metallic springs, elastomers, wire mesh, wire cable, pneumatic springs, elastomeric foams, and combinations of these or other cushioning devices.

Examples of active isolator mechanisms include servo-motor actuated mechanical linkages, variable resilience devices containing conductive or magnetic fluids, electro-dynamic force actuators, and pneumatic or hydraulic valve-operated actuators. The active isolator mechanisms are power operated in accordance with a command signal derived from feedback control signals."

(Ruzicka, 1968)

Flannelly (1966) makes a further distinction between conventional passive isolators and a unique passive isolator, the DAVI. He has this to say.

"Conventional shock and vibration isolators are fundamentally springs, and they begin to isolate only at a frequency which is the square root of 2 times the natural frequency of the isolator. To obtain low frequency isolation with a conventional isolator requires large static deflections; that is, a very soft spring. Many

helicopter frequencies are too low for practical vibration isolation by conventional means. The difficulty which is encountered is that the large static deflection allows the isolator to bottom during shock loads, thereby increasing enormously the load on the isolated item. The need exists for an isolator which can protect against very low frequencies without high static deflections.

"The isolation of decks, cargo pallets, passenger seats and other devices in which the supporting mass undergoes large changes is not practical with present isolators. Because the natural frequency is a function of the isolated mass, a passenger seat system, for example, which is isolated when fully loaded, could magnify the vibrations when lightly loaded or empty. To avoid these drawbacks, there is a need for an isolator which provides a given amount of isolation at a given frequency, independent of the magnitude of the isolated mass.

#### The DAVI

"Definition -- The Dynamic Antiresonant Vibration Isolator (DAVI) is a passive vibration isolation device which can provide a high degree of isolation at low frequency with very low static deflection. At a predetermined antiresonant frequency, the nearly zero transmissibility across a DAVI is independent of the mass of the isolated item. The DAVI differs from the vibration absorber concept in that the DAVI is a single-degree-of-freedom system which provides antiresonant transmissibility by rotatory inertial coupling between the input and output."

(Flannelly, 1966)

In the view of another, (Thompson, 1969) it can be shown that conventional passive isolation devices suffer from the large deflections associated with low natural frequencies,

resulting in unsuitable designs. Special passive devices are available which do provide the required isolation at the blade passage frequency while limiting the relative deflections to a greater degree than conventional systems. The more significant ones are: dynamic absorbers, dynamic antivibration isolators, and focal isolation systems.

Dynamic absorbers are presently used in the Chinook helicopter (CH-47) under the pilot and copilot seats. This type of device provides excellent vibration isolation at the frequency to which the absorber is tuned. However, variation in the excitation frequency will result in a detuning of the system. When detuned, the dynamic absorber can cause motions which are more severe than if no protection were provided. Finally, the auxiliary mass is generally of the same size as the mass to be isolated, which makes the approach impractical for the isolation of helicopter fuselages.

Dynamic Antivibration Isolators (DAVI) employ a concept of mass amplification through a lever arrangement. The required degree of isolation at the blade passage frequency can be obtained by a notch of isolation at the desired frequency. The notch frequency is a function of the auxiliary mass and the geometry of the lever arrangement, and is independent of the isolated mass. Although some degree of isolation is provided at frequencies larger than the notch frequency, a notch can be provided at only one frequency.

Focal isolation systems can be designed to provide a notch of isolation at a given frequency and some degree of isolation at higher frequencies. As in the case of both dynamic absorbers and dynamic antivibration isolators, variations in blade passage frequency will cause a detuning of the focal system.

The common disadvantage to all these systems is the inability to follow variations in blade passage frequency due to changes in rotor speed. In addition, the relative deflections resulting from maneuver loads and landing are said to exceed allowable limits and thus "bottom out" and provide no protection or isolation.

Active electrohydraulic systems, on the other hand, can provide notches of isolation at the blade passage frequency and any number of harmonics including the one per revolution excitation. They can be made to track the rotor speed so that notches of isolation are always located at the critical frequencies. Appropriate displacement control can be

introduced both to maintain the null position and to limit relative deflections during transients within acceptable limits.

(The above descriptions are adapted from personal communications with Mr. George Thompson of Barry Controls, 1969)

In addition to conventional devices, the DAVI, and electrohydraulic systems, Bies (1968) has proposed a hybrid vibration isolation system, consisting of passive elements and an active feedback loop, for the control of the conventional system's low frequency response. Available information suggests that system complexity and technical difficulties may combine to detract from the advantages of this approach. Its feasibility for practical application remains to be proven.

Another technique which is still in the experimental stage has recently been reported by Srinivasan (1968). His device, called the "Perissogyro", is a vibration absorber which consists of a gyrodisk at one end of a shaft and a cross pivot at the other. The utility of such a device will be to provide broad bandwidth effectivity by synchronizing the speed of the gyrowheel.

The foregoing techniques were mentioned to underscore the varied viewpoints, controversy, and developments in the field of vibration control. Even though we are not expert in this field and do not wish to pontificate, there are a few observations which can be made in the interest of polarization and clarity.

Most authors seem to agree that conventional passive systems are inadequate or unsuitable for helicopter applications. This appraisal does not hold true for the DAVI system, however, because of its unique characteristics. Furthermore, it is misleading to discuss the DAVI along with other passive systems, and then imply that conventional passive system shortcomings apply to it in like measure. This lack of apartheid merely serves to muddy the water.

If our evaluation is correct, the two leading techniques for vibration isolation are: some type of active system (probably electrohydraulic) and the passive DAVI. Therefore, the balance of our attention will be focused on the relative merits of these two types.

Those who foster active systems point out that they can be designed to respond with great flexibility across a

broad frequency band. Further, they can be made to track rotor RPM's so that notches of isolation are always located at the critical frequencies. Ruzicka (1968) lists the following ten virtues of active systems.

"The motivation for using active vibration and shock isolation systems is the potential achievement of performance characteristics that may include:

1. A very soft system for oscillatory dynamic excitations (providing natural frequencies substantially lower than conventional passive isolation systems).

2. Zero static deflection.

3. A very stiff system for applied loads of constant magnitude (static force or mass loading and sustained acceleration).

4. Return of payload to initial position during sustained loading.

5. Vibration isolation during sustained loading.

6. Independence of isolation performance to changes in payload weight.

7. The option of a unilateral or bilateral isolator dynamic stiffness characteristic.

8. A high speed of response.

9. Flexibility in shaping frequency-response characteristics.

10. Capability for introducing adaptive control using "early warning" or "preview" feedback signals."

(Ruzicka, 1968)



Proponents of the DAVI system maintain that it can accomplish the following:

1. Provide a high degree of isolation at low frequency with very low static deflection.
2. Notch the  $n/\text{rev}$  of the rotor, thereby isolating the dominant and most critical frequency to nearly 100 percent.
3. Provide a simple-to-install and maintain device which can be retrofited into existing helicopters.
4. Operate with no power consumption.
5. Provide strength to ensure crashworthiness for seats or other isolated components.
6. Provide relatively light weight isolation on the order of 1 to 2% of the isolated mass.
7. Provide efficient isolation in three axes.
8. Afford exceptional reliability.
9. Allow for simple manual or motor tuning over a 4 to 10 octave frequency range.
10. Isolate either individual components, such as panels, consoles, and seats; or ultimately, the entire fuselage.

The principal disadvantage of the active systems (compared to the DAVI) are: weight, reliability, unsuitability for retrofit, power requirements, greater complexity and maintenance costs, greater procurement costs.

The DAVI system, on the other hand, is said to be deficient in the following areas: inflexibility of response to RPM changes (and hence, frequency shifts), and the relative narrowness of the notched frequency zone. In addition, special passive devices are said to exceed allowable limits and bottom out as a result of maneuver loads and landing. Table 19 provides a summary comparison of DAVI vs an active system.

In-flight testing of the DAVI and of a comparable active system would be quite valuable in assessing the relative merits of each, and particularly in documenting the effects of such transient conditions as maneuver loading. If not too severe, an occasional brief transient

TABLE 19 SUMMARY COMPARISON\* OF ACTIVE AND PASSIVE  
VIBRATION ISOLATION TECHNIQUES

CHARACTERISTICS	ACTIVE	PASSIVE
	ELECTROHYDRAULIC SYSTEM	DAVI SYSTEM
Flexibility of response to changes in vibration frequencies	Good ability to track rotor speed (e.g. vibration frequency changes)	No frequency "tracking" ability
Frequency range of vibration isolation	Notches of isolation at several dominant freqs & multiple harmonics	Relatively narrow notched freq zone
Ability to isolate occasional large amplitude low frequency displacements	Relatively good	Relatively poor
Vibration isolation during sustained loading	Good	Insufficient data
Static Displacement	Zero	Very low
Adaptability to retrofit	Relatively difficult	Relatively easy
Initial Cost	More expensive	Less expensive
Flight Weight	Approx 10 % of isolated mass	Approx 1-2 % of isolated mass
Power Requirements	Electrohydraulic	None
Maintenance Costs	More	Less
Reliability	Lower	Higher

\* The contents of this table are adapted from information obtained from manufacturers of the two systems. The comparative descriptors used herein are subjective in some cases, merely reflecting the relative complexity of the two systems. Moreover, the list of characteristics is not exhaustive, nor are the items all of equivalent importance. Additional research and testing is required to determine more specifically (1) their relative importance: and ultimately, (2) the relative merits of the two systems. Only then can the most cost-effective one be selected for application to the helicopter vibration problem.

effect would probably do little harm to aircrewmembers. However, RPM changes are less straightforward.

Experience indicates that RPM levels are set prior to takeoff at near maximum limits and, for the most part, these are maintained throughout the flight. Moreover, data from flight manuals reveal that a characteristic variance of only about 10 percent is marked as the allowable range on the face of RPM meters. It seems logical, therefore, that pilots would tend to monitor RPM to keep it within specified limits, particularly if large drifts were to be accompanied by unwanted vibration. Giessler and Braun (1968a) report that for steady-state flights of CH-47A armed helicopters in Southeast Asia, 65.65 percent of the time is spent in the 230 to 240 RPM range, and 34.32 percent between 220 to 230. For cargo transport (Giessler and Braun, 1968b), 82.64 percent of the time was spent in the 230 to 240 RPM range; 16.45 percent between 220 and 230.

The foregoing suggest that RPM drift may be a less bothersome problem than might be presumed. This likelihood is even more evident if one considers the isolation notch of the DAVI (Figure 12) and the spiked nature of main rotor effects. The DAVI isolation notch is frequency specific at the nadir point where nearly 100 percent isolation is realized. As the notch widens, it provides less protection but broader coverage. It can be seen that a more gradual slope is experienced on the high frequency side of the nadir point, thereby providing more effective broad protection in the higher frequency zone.

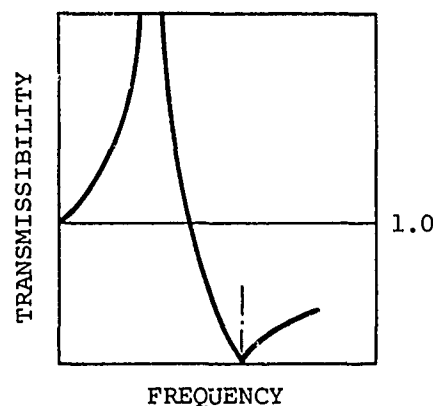


Figure 12 DAVI Vibration Isolation Curve

Rather than speculate about the relative merits of one technique versus the other, we recommend that the DAVI be installed in a test vehicle in order to determine the seriousness of maneuver loading and RPM frequency drifts. Both seat and instrument panel should be protected from multi-axis vibration. After in-flight test data are compared with data from non-isolated seats and panels we will have empirical proof of the deficiencies, or lack of them, in what is otherwise a highly promising technique. Once the degree of isolation afforded by the DAVI system is established, proponents of active or hybrid systems can be asked to demonstrate weight, cost, and power requirements to perform a comparably efficient job. If cost factors are sufficiently competitive, in-flight test data should also be considered for the most promising active technique.

#### Helicopter Flightcrew Helmets

Table 1 in the first section indicates that high intensity noise exposure is one of the major problems of concern to helicopter flight crewmen. In an earlier report (Ketchel et al., 1969) it was shown that commercial helicopter pilots consider the effects of noise exposure to be about equally as noxious as exposure to vibration. It was also shown that noise levels on the order of 115 dB are frequently experienced in helicopters, and that these are physiologically dangerous to both flight and ground crew personnel. Furthermore, noise is one of the agents which create fatigue, and noise has been shown to be detrimental to the performance of certain types of tasks.

Even though the above facts are well known to those who are familiar with helicopter flying, and even though many pilots realize that they are experiencing hearing losses, a number of commercial pilots refuse to wear uncomfortable ear protective devices. Both the physical discomfort of ill-fitting plugs and the lack of ventilation caused by poorly designed helmets are cited as unpalatable characteristics.

Camp (1966) investigated 36 ear protective devices in a unique study conducted for the Army's Aeromedical Research Unit at Ft. Rucker. The results of his study are summarized in the following conclusions:

"1. The amount of attenuation offered by any device is a function of frequency.

2. Greater attenuation values were obtained in the high frequencies.

3. All devices attenuated 4000 Hz and 8000 Hz no less than 14 db.

4. The most attenuation obtained at the two lowest test frequencies of 75 Hz and 125 Hz was 20 db.

5. The greatest attenuation at any one test frequency was 50 db at 4000 Hz.

6. The quartile and decile values as a function of frequency fell into three general groups. The values for low frequency group of 75 Hz, 125 Hz, and 250 Hz, and the high frequency group of 4000 Hz and 8000 Hz had a variation no greater than 4 db among the test frequencies. In contrast to this homogeneity of values was the heterogeneous quartile and centile values of the mid-range frequencies of 500 Hz, 1000 Hz and 2000 Hz."

In a subsequent study (Camp and Keiser, 1967) the Navy's SPH-3 (modified LS) helmet was compared to the then popular APH-5. Taking cognizance of the high noise levels experienced by Army personnel, the report has this to say.

"Analyses of acoustic spectra in Army aircraft have shown that the sound pressure levels are usually much greater than the Army Technical Bulletin T. B. Med 251, 25 January 1965, criterion for the initiation of a hearing conservation program. The deleterious effects of high sound pressure level acoustic noise on military personnel are manifest in various ways. For example, there may be masking or interference with voice communications to the extent that the efficiency of military operational groups is impaired. Also, the noise may jeopardize the health and efficiency of Army personnel by causing permanent or temporary hearing losses. The gravity of the noise problem in Army

aviation is indicated by the fact that there is a frequent occurrence of permanent and temporary high frequency hearing loss of various degrees among Army aviation personnel.

"The Army does provide earplugs for ear protection. However, this type of ear protective device is inadequate for all personnel under all operational conditions. There is a need for more sound attenuation in some environments of high sound pressure levels. Also, it is estimated that a large number of personnel avoid the use of earplugs because of discomfort and other reasons. In view of the inadequacy of earplugs alone as a universal ear protector and their lack of acceptance by the user, it is imperative that efficient sound attenuation devices be an integral part of the flight crash protective helmet."

(Camp and Keiser, 1967)

These observations confirm our own and support the comments noted in Table 1. Moreover, the table shows that both SPH-3 helmets and Gentex earcups are widely recognized for their comfort and effectiveness. The development of such devices and greater emphasis on overall acoustical design improvements in helicopters indicate that the impact of noise on aircrew performance can be minimized. If improvements continue in this area, even greater attention can be focused on vibration, which is considerably more difficult to alleviate, and to the other significant design problems such as ventilation, lighting, instrumentation, and temperature control.

In the Camp and Keiser study, it was shown that the APH-5 was superior at only two frequencies (and by a narrow margin in these instances) 0.3 dB at 4,000 Hz and 2.0 dB at 6,000 Hz. "For the six test frequencies between 75 and 2,000 Hz, the SPH-3 had greater attenuation values. The improvement over the APH-5 at 75, 125, 250, 500, 1000 and 2000 Hz was 5.9, 6.0, 9.0, 17.6, 8.0 and 7.3 dB, respectively." Comparative graphs of the attenuation effects of the two helmets are reproduced from the Camp report in Figure 13.

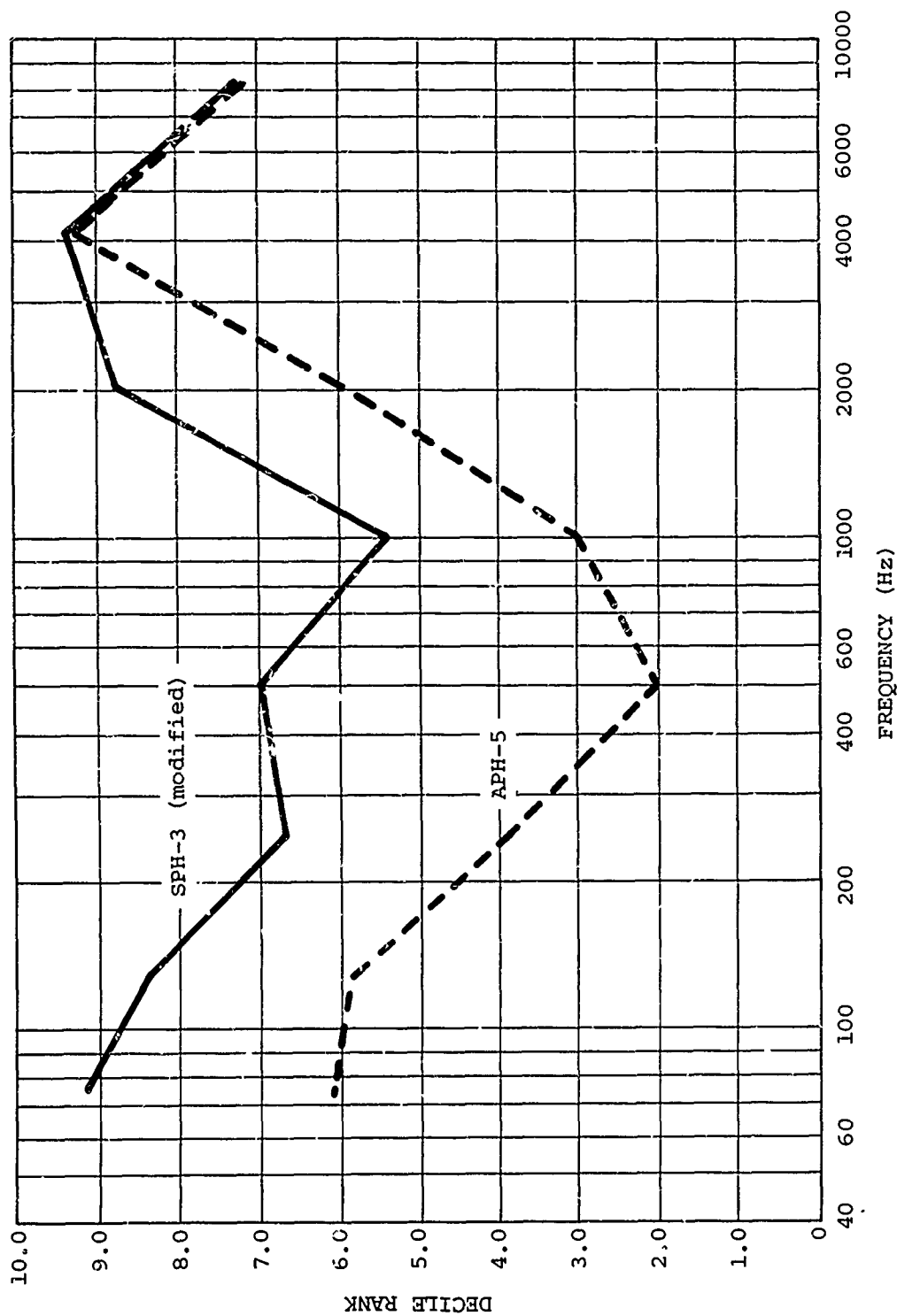


FIGURE 13 DECILE RANKS OF REAL-EAR ATTENUATION VALUES OBTAINED WITH THE APH-5 AND SPH-3 (M) HELMETS

(from Camp & Keiser, 1967)

## Seat Design

The three primary design considerations for aircraft seats are crashworthiness, comfort, and utility. Of these, crashworthiness and utility are of the most obvious importance, and therefore, have received the greater share of design attention. However, since these two topics are not directly within the purview of the present study, they are afforded only tangential treatment, and the comprehensive work of Turnbow and his associates (1967) is recommended for a more detailed discussion. For our purposes, utility refers to the appropriateness of a seat for its intended use. Crashworthiness refers to the structural characteristics of a seat and includes such factors as rigidity, integrity, anchorage, and crash force attenuation.

The not so obvious importance of comfort in seat design has been cited by Turnbow and is of foremost concern to us because of its impact on fatigue. Recognizing the relationship, Turnbow has this to say about seat comfort and pilot fatigue.

"The comfort of an aircraft seat is a safety-of-flight factor rather than a crash-safety-design factor. An uncomfortable seat can induce pilot fatigue in a short period of time. Pilot fatigue is an indirect cause of aircraft accidents. Comfort is thus of primary concern and must not be compromised."

(Turnbow et al., 1967)

Table 1 in the first section of this report indicates that complaints about seat design in military helicopters are many and varied. As one might expect, the situation is not greatly improved in non-military circles. In an earlier study by Ketchel et al. (1969) it was reported that about one-third of commercial helicopter pilots condemn seat design, and that a number of them carry personal seat cushions.

Among the discrepancies voiced about seat design, the following six are most often heard.

1. Lack of adjustment in the up/down (z-axis), forward/back (x-axis), and pivot or tilt angle directions.
2. Inadequate shoulder and chest support. This is particularly troublesome in those helicopters which characteristically cruise in a pitch-down attitude.



3. Circulation interference. A number of helicopters have rigid bars or crossmembers which press against the thigh and inhibit circulation. For example, the SH-3's seats have rectangular pan-shaped bottoms into which crushable cushions are placed. The upper front ridge of the pan has been said by crewmembers to cut circulation when the cushion compresses. Other helicopters have webbed passenger seats which are supported by a horizontal metal bar. In either design the discomfort can be considerable after a comparatively short ride.
4. Inadequate cushioning. Seats which are too hard cause buttock fatigue and are said to be quite uncomfortable after about 1 to 2 hours. On the other hand, those which are too soft can amplify the effects of a crash and can cause severe damage.
5. Poor ventilation has been mentioned as one of the reasons why some crewmembers prefer webbed seats.
6. Lack of a headrest and lack of support in the lower lumbar region. Obviously, an appropriate headrest should not unduly inhibit freedom of movement; nor should it aggravate or amplify the amount of vibration transmitted to the head. The desirability of lower lumbar support which would protect against the effects of vibration and relieve back strain seems evident. Whether or not support would accomplish these goals remains open.

In addition to these six problems, a number of basic human factors and structural design defects are often mentioned in discussions about seat design. For instance, the seats in some military helicopters can lower unexpectedly because of disengagement of the locking pin. The troop commander's seat in the UH-46D is said to lack a safety belt and should not be occupied during takeoff or landing. Seat adjustment in the CH-53A must be exercised with care so as not to interfere with the positioning of the cyclic stick. The sonar operator in the SH-3 must raise himself partially and twist around in an awkward position to view the hoist mechanism, which must be seen through a poorly located window at his back. His partner's seat is situated such that illumination from the single dome light above them is blocked by an overhead extrusion.

Such examples are by no means exhaustive, nor are they intended to fault a particular aircraft manufacturer. We do suggest that inadequate seat design is commonplace in most

contemporary helicopters. Although functional utility and crashworthiness are important considerations, experience indicates that comfort is the requirement most often ignored. In summary, it can be seen that all three requirements have impact on safety, while functional utility and comfort relate to efficient performance and fatigue reduction as well.

Turning now from the negative comments and problems in seat design, there is both general and specific design guidance available. We have already mentioned the comprehensive work of Turnbow and his associates (1967). Another significant report was published by Burse in 1966 in an Army sponsored research project. He describes seat design objectives for the gunner/observer in terms of five general human factors requirements.

- "(1) preventing interference with performance of the crewman's primary mission;
- (2) preventing safety hazards;
- (3) reducing fatigue;
- (4) providing compatibility between the seat unit and clothing or other equipment worn by the crewmen;
- (5) providing as much comfort for the crewmen as possible."

Further, Burse lists design criteria in the following four areas which are said to be useful in meeting these requirements.

- "(1) dimensions and contour of the sitting surface;
- (2) characteristics and dimensions of cushioning and covering materials;
- (3) location of the seat unit and its supporting structure within the aircraft;
- (4) clearance of the seat unit and its occupant from aircraft structure."

(Burse, 1966)

Among his specific recommendations for design of the gunner/observer seat in the UH-1 series helicopter are these:

- Seat dimensions should accommodate and protect the 5th to 95th percentile fully equipped crewman.
- The contour of the seat pan should be flat, but with the side and back edges curved upward one inch.
- The crotch protector should have a slight forward curvature and be hinged to deflect forward. It must also have a positive stop to prevent rearward movement.
- The seat cushion should be a minimum of one inch under the ischial tuberosities to allow adequate blood circulation in the buttocks.
- All edges should be rounded smoothly and covered.
- Cushion thickness should be about 3 to 3.5 inches (Bondurant, 1958; Whittenberger, 1959). Whittenberger recommends a 3.5 inches thick cushion of polyether urethane foam of 2.1 to 2.5 pounds per cubic foot density as the best compromise between comfort and resistance to "bottoming".
- Whittenberger further recommends the equivalent of Good-year C-25 hard polyether foam, based on this material's uniform compressability.
- Standard heavyweight ballistic nylon fabric is recommended for covering the cushion along with an impermeable underlayer to prevent moisture absorption.

These examples of recommendations found in Burse's study are both aircraft and application specific. However, some of these and others which are made in his report have general appeal, being either directly usable or suggesting a point of departure for comparison to other design applications.

Turnbow's recommendations are based on a broad review of aviation requirements, covering both fixed and rotary wing aircraft. He takes a particularly dim view of "lap belt only" restraint systems and of side-facing seats. He recommends rearward-facing seats as a first choice, considering forward-facing ones acceptable, however, if all occupants are provided with upper and lower torso support.

In regard to seat cushion requirements, Turnbow suggests that they be used for comfort only, and not as a device to absorb energy in the vertical direction. Further, he recommends that "the thickness of soft, elastic foam, necessary for a

comfort cushion, should not exceed 1.5 inches if a properly contoured cushion is used."

Turnbow states that load-limiting crushable cushions are not practical for rotary wing aircraft because of excessive thickness requirements. He recommends instead that load-limiting net-type cushions be used. In his words:

"This type of cushion serves the same purpose as the crushable cushion; however, a net material is stretched over a contoured seat frame and the body is supported by diaphragm action in the net rather than by compression of a crushable material. The net-type cushion might more properly be called a net support. If a net support is used for load limiting in the seat, then its rebound characteristics should be such as to limit the return movement from the point of maximum deformation to 1-1/2 inches."

(Turnbow et al., 1967)

Another area of concern to seat designers is the need for an emergency escape system. Strictly speaking, this has little to do with vibration effects and will be mentioned but briefly. Our reason for introducing the topic at all concerns the implications posed by escape systems on body restraint techniques and on vibration isolation devices. Both must be amenable to whatever escape system is considered and both are related to the effects of vibration.

In general, helicopter manufacturers are keeping an open mind about emergency escape systems and have not yet agreed on a suitable design. One design that showed some promise was discussed in a paper by Weinstock in 1964. He proposed a novel L-shaped escape trajectory which would thrust the escapee laterally from the fuselage to a distance beyond the rotor tips by means of a ballistic catapult. Subsequently, a rocket charge would thrust the passenger upward to a height sufficient for safe recovery by parachute. Although dynamic tests of a full scale mock-up system gave encouraging results, the physiological effects of two contiguous thrusts in the y and z axes was noted as a problem requiring additional research. Nevertheless, the need for including some type of emergency escape system persists and is underscored by the increased use of helicopters in low level offensive strikes.

Unfortunately, we have only been able to touch on some of the problems in seat design, intending merely to indicate the scope of the considerations involved and a few examples of design recommendations. There is obviously a great deal to be accomplished in this area.

### Ventilation and Air Conditioning

Excessive cabin temperatures are considered to be one of the most onerous of problems faced by helicopter crewmen. Heat undoubtedly causes physical and mental fatigue, and in general, adds its burden to an already difficult environment. Contemporary helicopters use ram-air ventilation, thereby achieving some relief during forward cruise. However, during warm-up, taxi, and while engaged in extended hover, cockpit and cabin heat can be quite burdensome.

In the summertime, windows and doors are typically left open to relieve the temperature. This has the disadvantage of admitting undesirable noise and exhaust fumes. In fact, many helicopter pilots exhibit significantly greater hearing losses in the ear next to the window side of their seat.

Air conditioning would be a welcome advancement in helicopter design, if it could be realized without undue weight and power penalty. At the very least, the feasibility of small, efficient air conditioning equipment should be explored, and more efficient ventilation equipment should be sought. The payoff in crew comfort and added efficiency would probably be well worth the effort.

## SECTION 6                      SPECIFICATIONS, STANDARDS, AND RESEARCH REQUIREMENTS

### Duration of Exposure

The preceding sections have dealt with helicopter missions, crew tasks, and the effects of vibration on performance. We now come to one of the central and most thorny questions confronting us. What limits should be set on the length of exposure to vibration both to protect the health of crewmen and to ensure adequate levels of performance?

To answer this question we must consider fatigue and the biomedical effects of long term exposure to vibration. Unfortunately, these are elusive quarry. Both are difficult effects to measure, and there are few reliable ground rules to guide us.

### Biomedical Effects of Long Term Exposure

The Seris and Auffret study (1967) is one of the few published reports which directly relates helicopter vibration exposure to back pain. The authors suggest that long duration exposure to vibration amplitudes and frequencies similar to those recorded in the Super Frelon helicopter are likely to cause back pain in over 85 percent of exposed pilots. As shown in Section 2 of this report, acceleration peak levels for the Super Frelon are found between 0.3 and 0.4 g's at approximately 20 Hz. The Seris and Auffret report summarizes the work of five French studies and has this to say.

"According to clinical studies of Missenard and Terneau, and of Pellet in 1957, of Fabre and Greber in 1959, Montagard, Sais and Guiot in 1961, and particularly according to Sliosberg's thesis in 1962, the relationship between vertebral pain, lumbosciaticas and helicopter piloting is clearly established. Sliosberg's investigation relates to 128 pilots. Among these, 112, i.e., 87.5 percent, had pain; generally the pains begin

with the 300th hour of flying time. However, pilots with pathological condition of the spinal column began to suffer earlier, after 50 or 100 hours of flying time. An extended mission, or a difficult one, evokes pain whose duration is a function of the pattern of the flights. Average figures that are cited in the study as threshold of appearance of difficulties are 4 to 5 hours per day, 40 to 50 hours per month...

"What may be the consequences for the pilot? The Sliosberg study, the papers by Dieckmann, Goldman and von Gierke, and the experiments of Coermann, Clark, White, Hornick and Parks allow us to make a prediction. On short range, that is to say, during flight and particularly at the end of a 3-to-4 hour mission there is noted essentially phenomena of diffuse fatigue with a more or less pronounced drop in performance.

"Recovery is more or less rapid, depending upon the degree of fatigue and, of course, upon the rest available to the crew...

"In the long range, helicopter pilots suffer back pain in 87.5% of the cases after 1 or 2 years of operation.

"Of the 128 pilots studied by Sliosberg, 35 complained of neck pain, 54 of back pain, and 96, i.e., 75 percent, of lower back pain, 11 of them with distinct sciatic radiation. The clinical signs are generally fairly clear and go from simple limitation of movements of the trunk to perivertebral muscular contraction and the classic symptoms of sciatica. Radiological examination reveals an abnormal frequency of lumbar scolioses, and Montagard points out discrete signs of arthrosis also.

"The evolution is a function of the rhythmic pattern of flight. The threshold of appearance of pain is at more than 4 to 5 hours per day, more than 40 to 50 hours per month..."

(Seris and Auffret, 1967)

The Seris and Auffret findings are both refreshingly straightforward and impressive. However, they are by no means conclusive. A recent survey of pilots at five helicopter airways companies (Ketchel et al., 1969) uncovered a range of unfavorable comments about helicopter noise and vibration. Participating commercial pilots typically experienced 60 hours of flying per month and have accumulated an average total helicopter exposure of approximately 4,500 hours. Responses often included mention of fatigue, headache, backaches, and back problems which caused lost flying time. In one company, 74 percent of a 27-pilot sample felt that noise and vibration are about equally onerous. Yet, most of the comments seemed to express annoyance and displeasure, rather than complaints of serious disability. Perhaps Seris and Auffret are suggesting much the same thing. They do say that "recovery is more or less rapid, depending upon the degree of fatigue and ... rest available ..." More research is obviously needed to determine the seriousness of reported disabilities, and to identify those precipitating conditions which are likely to cause chronic complaints or permanent injury.

#### Fatigue

In a recent report on factors affecting army flight crew personnel, the Life Sciences Research Office of the Army (1969) has specifically expressed concern about rotary wing flight crew fatigue. They have this to say.

"It has been suggested that the demands of helicopter operations in the combat zone can lead to clinically recognized "combat fatigue" or "pilot fatigue". The early identification of both these and related forms of "fatigue" is a pressing problem for the aviation medical officer ...

"The occurrence and extent of performance impairment in helicopter flight crew personnel are not adequately documented."

The term "combat fatigue" is often thought of as resulting from psychological stress, rather than physical factors. Indeed, both mental and physical fatigue tend to impair crewmember performance. The mind/body relationships are so interwoven that the separate contribution of each



TABLE 20 FATIGUE CHARACTERISTICS, SYMPTOMS, AND CAUSES

PHYSICAL FATIGUE CHARACTERISTICS	MENTAL FATIGUE SYMPTOMS
<p><u>INCREASED</u></p> <ul style="list-style-type: none"> <li>• Reaction Time</li> <li>• Blood Lactic Acid</li> <li>• Lag in Pupillary Response Time to Light</li> <li>• Time of Visual Accommodation</li> <li>• Loss of Electrolytes through 'sweat'</li> <li>• Excretory Organs</li> <li>• Urinary Corticosteroids and Catecholamines</li> <li>• Instability of Neuromuscular Coordination</li> </ul>	<p><u>INCREASED</u></p> <ul style="list-style-type: none"> <li>• Irritability</li> <li>• Susceptibility to Err</li> <li>• Anxiety</li> <li>• Tendency to Insomnia</li> <li>• Susceptibility to Depressive States</li> <li>• Tendency to Withdraw from Hobbies and Avocational Social Undertakings</li> <li>• Tendency to Use Pharmacologic Crutches (Ethyl Alcohol, Chain Smoking, Tranquilizers, Barbiturates, Bromides, Nerve Tonics, etc.)</li> </ul>
<p><u>DECREASED</u></p> <ul style="list-style-type: none"> <li>• Strength</li> <li>• Blood Glucose</li> <li>• Ability for Rapid Binocular Fusion</li> <li>• Muscle Tonus</li> <li>• Circulating Blood Volume</li> <li>• Muscle Glycogen</li> </ul>	<p><u>DECREASED</u></p> <ul style="list-style-type: none"> <li>• Attention Span</li> <li>• Libido</li> <li>• Recent Memory</li> <li>• Cooperativeness</li> <li>• Acceptance of Constructive Criticism</li> <li>• Interest in Personal Care or Hygiene</li> <li>• Sometimes an Extreme of the Reverse</li> <li>• Gastrointestinal Efficiency</li> </ul>
<p><u>CAUSES</u></p> <p>Temperature, humidity, color, light intensity, noise, vibration, odors, gases, barometric conditions, ozone, protracted immobility, excessive loss of sleep, illness, and advanced aging changes</p>	<p><u>CAUSES</u></p> <p>Repeated sleep inadequacies, excessive psychosensory task demands, time-pressure stresses, frequent unanticipated interruptions of work procedures, excessive task loading with trivia, frequent emergencies or false alarms, inadequate compensation for task, inadequate recognition of accomplishment, inadequate task challenges and interest, ambiguous rules and procedures, interrupted family life, family medical and social problems, personality clashes with coworkers or supervisors, nature of punishment for omissions and commissions, monotonous and boring circumstances, and minor discommodating afflictions (pruritis, refractive error in spectacles, certain allergies, etc.)</p>

(Adapted from Mohler, 1965)

is often difficult to isolate and identify. Table 20 is adapted from a report on these topics by Mohler (1965). It lists many of the measurable characteristics of physical fatigue, the symptoms of mental fatigue, and potential causes of both.

More recently, Austin et al. (1967) have developed some techniques for monitoring Navy carrier pilots who are engaged in flying high-risk combat missions in North Vietnam. In addition to cardiorespiratory response data, they found: "The phosphatidyl glycerol fraction of the plasma phospholipids became elevated during the combat period, as did the phosphatidic acid, while the cardiolipin level remained relatively constant." These changes in blood components were statistically significant for combat pilots when compared to other stress states or to control subjects, and are recently found measurable indicators of physiological stress.

Frazer (1955) would agree that fatigue is capable of objective measurement. Even so, he cautions that it is a complex problem which refuses to yield to "isolated measures of function, e.g., visual acuity." He also notes that it "affects high-grade performance long before there are signs of physiological exhaustion ..." Fortunately, the complexity and difficulty of the problem have not diminished widespread interest in the effects of fatigue. Continued efforts should be made to identify the conditions which cause fatigue, to describe its characteristics and symptoms, and to establish its effects on performance.

#### Combat Missions and Long Duration Flights

The Navy/Marine Corps helicopter missions described in Section 3 typically last for from 2 to 4 hours per sortie. However, the number of missions per day can be quite variable across commands. It is largely a function of tactical requirements and local commander option. In 1956, the recommended maximum monthly exposure limit for Army helicopter pilots was set at 90 hours. In 1969, exposure had risen to from 80 to 200 hours, with visits to the flight surgeon required after 120 to 140 hours. It is assumed that Marine Corps experience approximates that of the Army in regard to variability, length of missions, and total hours flown per month.

Variability of exposure is even more pronounced when considering the lot of non-pilot crewmembers. In some cases pilots are considered to be "safety-of-flight" personnel and, as such, may be assigned a more favorable work/rest cycle than less fortunate crewmen. For example, after 4 hours of ASW flying, the pilot and copilot may be relieved, even though sonarmen, crewchiefs, or others are required to duplicate or even triplicate the mission. One may hope this practice is atypical and representative of only a small portion of commands.

With respect to long duration flights, it is misleading to assume, as some imply, that the availability of alternate crewmembers on long duration flights somehow reduces the effects of exposure to vibration. Vibration acts largely the same on everyone, whether on or off watch. The benefit of being relieved of duties is mainly that it affords a period of relaxation, of a specific type. It does not provide relief from exposure to the ambient condition. It is, therefore, not surprising that crewmen on a recent 18-hour transatlantic helicopter flight experienced severe headaches at the end of their trip. What is surprising is that headaches occurred approximately 12 hours following the end of exposure. Furthermore, it has been noted that passengers or crewmen who are not occupied with some meaningful task are more prone to motion sickness. This factor is particularly important in troop transport missions, in which combat personnel are flown directly into a fire fight.

#### Recommendations by International Organization for Standardization

Working Group 7 of IOS Technical Committee 108 has generated a standard on vibration exposure limits which can be widely applied. It relates a range of exposure durations (1 minute to 8 hours) to frequency and acceleration levels. The limits which are established on the basis of "fatigue-decreased proficiency", are admittedly tentative at this initial stage.

The authors of the standard acknowledge that it deals with complex factors and, lacking firm experimental support, it is necessarily based upon limited quantitative data. Its stated purpose is to "facilitate the evaluation of comparable data for further research" and to provide for a "provisional judgment."

Commenting on the standard, Guignard (1967) points out that its variable limits, which are related to both frequency of vibration and duration of exposure, acknowledge that performance decrements can result from an interaction of time-dependent (fatigue effects) and time-independent influences. He states that "the latter are mostly related to body resonance phenomena ..." and that "decrements in performance due to mechanical effects are strongly dependent on frequency." Further, Guignard notes that there is general agreement that psychomotor tasks requiring eye/hand coordination are most easily degraded by whole body vibrations in the 4 to 8 Hz band. Note Figure 14 which shows that 4 to 8 Hz is the least tolerable of all frequency ranges.

In Figure 14 we have marked the frequency range for main rotor effects and have indicated the 0.15g limit specified in MIL-H-8501A for pilot, crew, and passengers. These data show that at 0.15g, 10 Hz vibration can be tolerated for 1 hour, 16 Hz for about 2.5 hours, and 30 Hz for over 8 hours. In addition, Working Group 7 recommends that the allowable acceleration levels be increased no more than 6 dB to set an upper boundary. This limit will ensure avoidance of exposures which could be hazardous to health. To establish more comfortable boundaries, 10 dB is subtracted from the applicable acceleration limit.

An alternate treatment of the data is presented in Figure 15. Here it can be seen that on a 4-hour mission, such as one typically flown during ASW, acceleration should be less than 0.1g for frequencies in the 8-15 Hz range. For frequencies in the 16-31.5 Hz range, the tolerable limit is approximately 0.15g. Table 21 sets forth recommended acceleration limits for these cases.

Table 21      APPROXIMATE ACCELERATION LIMITS FOR A  
4-HOUR MISSION

8-15 Hz	Upper Limit	0.12g	(+ 6 dB)
	Recommended	0.07g	
	Comfort Level	0.032g	(- 10 dB)
16-31.5 Hz	Upper Limit	0.23g	(+ 6 dB)
	Recommended	0.15g	
	Comfort Level	0.07g	(- 10 dB)

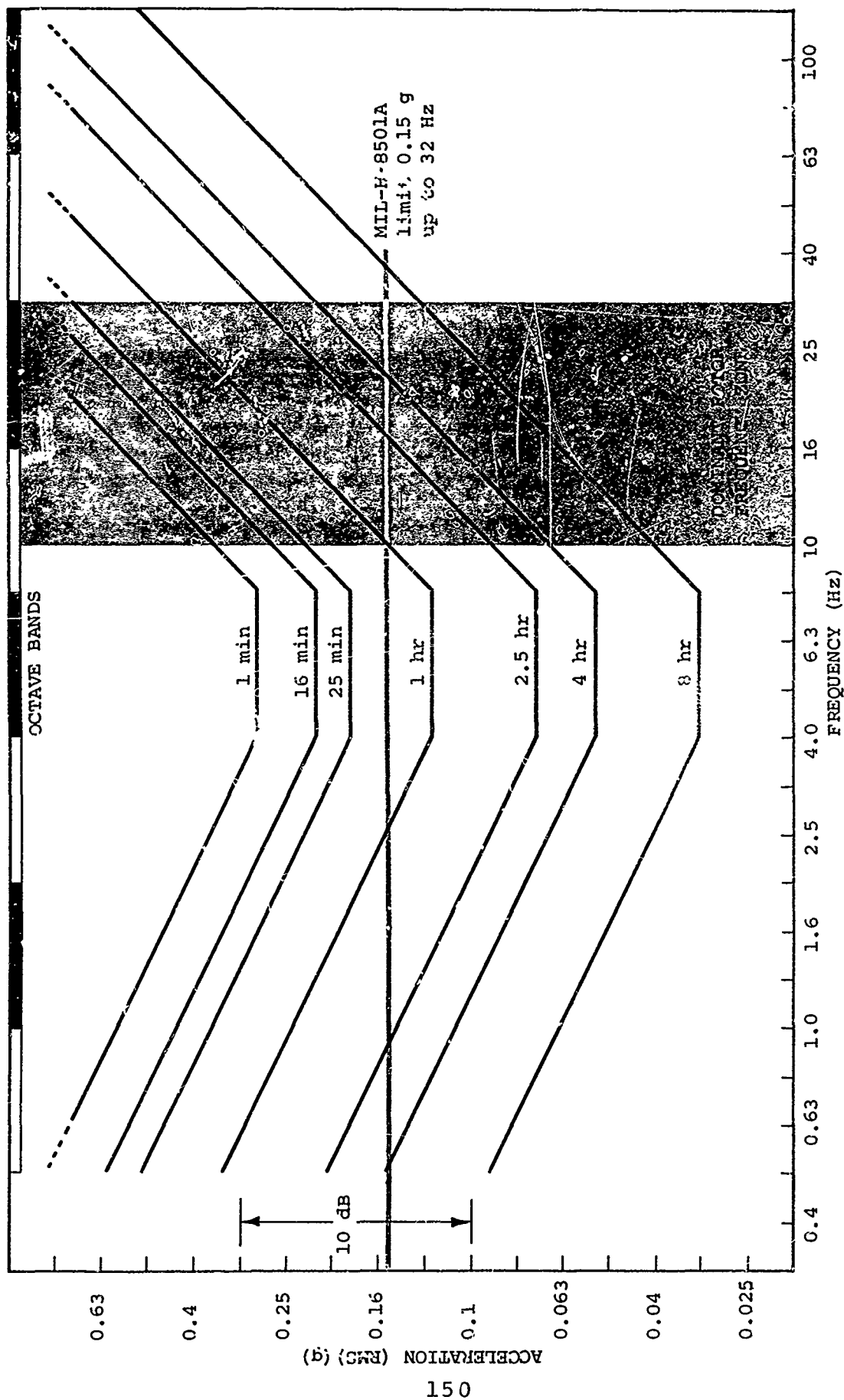
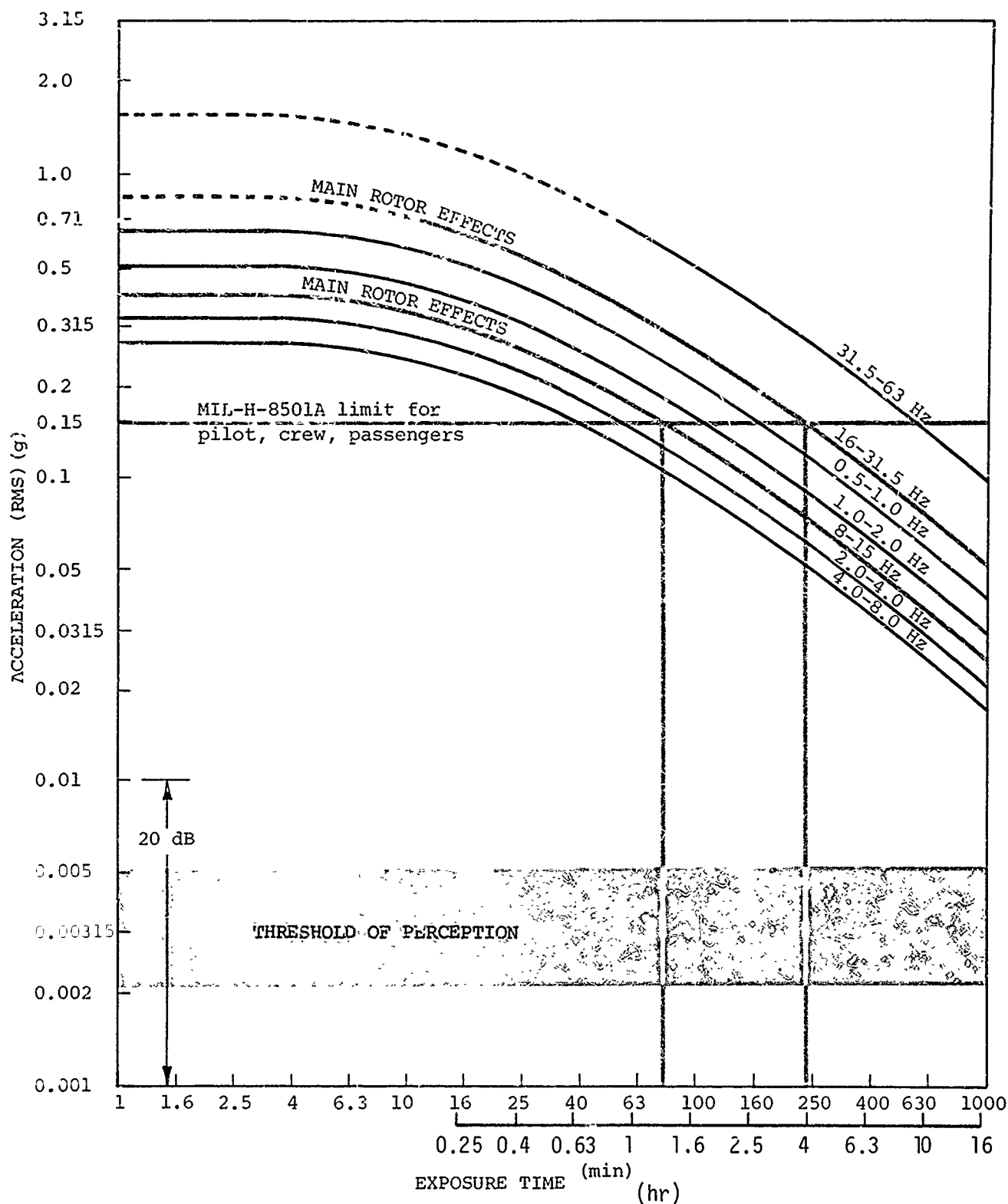


FIGURE 14 VIBRATION EXPOSURE CRITERIA AS A FUNCTION OF FREQUENCY (FATIGUE-DECREASED PROFICIENCY BOUNDARY)  
(Adapted from Working Group 7, IOS/TC 108 data, August 1968)



To obtain:

"Exposure Limits" acceleration values to be multiplied by 2 (6 dB higher)

"Reduced Comfort Boundary" acceleration values to be divided by 3.15 (10 dB lower)

FIGURE 15 VIBRATION EXPOSURE CRITERIA (FATIGUE-DECREASED PROFICIENCY BOUNDARY) AS A FUNCTION OF EXPOSURE TIME AT THE DIFFERENT FREQUENCY BANDS (SINUSOIDAL VIBRATIONS)

(Adapted from Working Group 7, IOS/TC 108 data, August 1968)

The recommendations set down by Working Group 7 suggest that military helicopters are being used in a manner which subjects crewmen to conditions which are detrimental to health, if not hazardous. Missions often last for periods of 4 to 8 hours with little or no rest between sorties. Dominant rotor frequencies range from 10 to 30 Hz and acceleration amplitudes range from about 0.1 to 0.4g or more. In a number of instances these combinations are clearly beyond the limits of MIL-H-8501A.

The International Organization for Standardization recommendations also suggest that MIL-H-8501A is remiss in its failure to account for time-dependent effects. Setting a level, such as 0.15g, for all frequencies up to 32 Hz is too gross to be of much practical benefit.

Turning to the new standard, it, too, must be regarded with a healthy degree of skepticism. Again, a comment by Guignard helps to set the standard in proper perspective.

"Although technical objections can undoubtedly be raised to limits expressed in this form, and it is recognized that there will be many situations in which they are not very meaningfully applicable, it is nevertheless considered that some guidance, even if it is based on incomplete data, is better than none. All criteria and limits of this kind must be interpreted with a degree of common sense, with the proviso, moreover, that they are ever subject to revision in the light of new knowledge of the human response to vibration."

(Guignard, 1967)

### Research Requirements

In this report we have taken a broad view of the world of military helicopters. This has been necessary for two reasons. First, only a general view can encompass the myriad of factors and interacting variables. Second, our main task, to determine the effects of vibration on crewmen, can be brought into proper focus by placing it in a larger frame of reference.

It seems fundamental that, in order to determine the effects of vibration, the nature of that vibration must be defined. Moreover, both the physical characteristics of vibration and the duration of exposure are of cardinal importance. The nature of helicopter vibration was discussed in Section 2. Exposure effects were treated in the preceding part of this section and in Section 4. In addition to these matters, it was necessary to discuss the missions, tasks, and equipment of those subjected to the vibrational environment. Sections 3, 4, and 5 have been devoted to these topics. However, our coverage is not yet complete.

We must now consider the concomitant issues in counterpoint with the main theme, and indicate what research is necessary to fill gaps in existing knowledge. These matters are treated in the remainder of this section. The restricted treatment given to each subject is a function of resources and the scope of this effort. It does not imply relative importance.

#### In-Flight Testing of the Vibrational Environment

We have already emphasized that one of the most important prerequisites to definitive research on the effects of helicopter vibration is adequate knowledge of the vibrational environment. This information is not available. Consequently, we are forced to speculate about both the impact of vibration on performance and about the very nature of that vibration. Inability to specify the most important independent variable is at best an unattractive burden.

To remedy this situation, the following steps are outlined and recommended for execution.

1. Collect vibration data on new aircraft either from the airframe manufacturers or at cognizant military commands. These data should include recordings of three axis (x, y, and z) frequency and acceleration levels throughout a specified mission. The most appropriate missions would comprise the ones representing the most frequent Navy/Marine Corps use of the helicopter in question.
2. In-flight recordings should be made at various Navy/Marine Corps maintenance facilities. These bases and their helicopters should be representative of the spectrum of field conditions to which helicopters



are typically exposed and various aircraft life cycles.

3. A quasi-random sampling plan should be generated, and in-flight recordings of vibration and other ambient variables should be gathered. Data collection should be made for the typical mission profile of each of these helicopters:  
SH-3D (ASW), UH-2C (SAR), UH-46D (Vertical Replenishment), CH-53A (Heavy Transport), and AH-56A (Assault). If the last is unavailable, use the UH-1E (Assault).
4. Data from helicopters used and maintained in field condition should be compared with baseline data from new aircraft.
5. The results should be used to assess both biomedical and performance effects and to establish a basis for man-in-the-loop simulation.

The above recommendations merely sketch some of the important considerations. Additional data collection is not precluded from this plan. In fact, noise, temperature, interior cockpit lighting, and human engineering design notations should also be taken during the data collection period. In this way chronic problems can be identified, and user complaints can be compared with measured environmental conditions.

#### Vibration Isolation

In addition to the above plans, it is recommended that the effectiveness of vibration isolation be tested on seats, panels, and console displays. In-flight testing of multi-axis vibration isolation devices is needed for comparison with the data collected on field-condition helicopters. A number of material benefits will accrue from this direct comparison. It will, for example, help to determine the relative effectiveness of various isolation techniques, the need for an automatically tunable system, and the need for rotor isolation as compared with individual component isolation.

Related topics should be identified for concurrent investigation. Malfunction cues, which are said to be provided by abnormal vibration, should be evaluated. Are they of real importance to pilots and maintenance crews? How often are such cues felt? Are they considered to be a routine part of the job

by most pilots? If the pilot is isolated from such cues could the same information be detected and displayed by an alternate means?

#### Medical Record Keeping

At the outset of the present study, it was expected that medical records could be collected conveniently and summarized to help correlate work/rest cycles either with accidents or with reports of adverse biomedical effects. It was also hoped that summary statistical records would be available so as to compare the physical condition of groups of helicopter pilots with fixed-wing pilots at the time of leaving the service.

Unfortunately, this has not been possible. Either the required records do not exist, or they are not available in a usable form. Even though hundreds of accident reports are filed, sorting through them, summarizing, and correlating findings would be a major undertaking. For example, an investigation of fatigue as a contributing factor to accidents would involve isolating the accidents for which fatigue has been identified as a causal factor. The next step would involve separating those accidents attributed to equipment fatigue (metal fatigue) and those due to pilot fatigue (mental or physiological). Further, the latter group would probably be small, not because of a lack of cases but more likely because they would be buried under some vague heading, such as "pilot error".

Because our experience with this problem has of necessity been a brief one, our first analysis may be somewhat inaccurate. If so, we would be pleased to acknowledge the error. If, however, our initial impression is valid and appropriate summary records do not exist, we recommend that they be systematically collected. This effort would be perhaps the most efficient and inexpensive means to establish long term biomedical effects data. These, in turn, would be of material aid in assessing the need for vibration isolation devices and for verifying the adequacy of standards. The recommendations of Working Group 7 require supporting evidence of this kind for proper evolutionary growth. Moreover, MIL-H-8501A cannot be adequately revised in the absence of reliable and valid medical and performance data.

## Photic Stimulation

A medical problem of a somewhat different nature is that of photic stimulation. This problem was mentioned by Berry and Eastwood in 1960 and by other authors before them. Melton et al.(1967) puts it this way.

"The medical literature is replete with apocryphal, anecdotal and documented reports dealing with the problem of alteration of consciousness, disorientation, nausea, distraction, annoyance or other symptoms related to flashing or flickering lights in the environment. The possibility of a compromise of air safety by such an effect has naturally stimulated several investigators to examine the problem as it exists in the aviation environment."

We will comment briefly on three significant studies in this area which have been published since Berry and Eastwood. In 1963, Johnson studied 102 pilots at the Ream Field Naval Air Station. He concludes that flicker is a source of annoyance or irritation to about one third of experienced helicopter pilots. "The problem is usually reported to be only minor or moderate in degree, but on occasion it may be severe enough to cause an accident or near accident."

Melton et al. (1967) studied 10 subjects, stimulating them with a Grimes red rotating beacon (1.5 FPS), an Air Guard strobe light (1.0 FPS) and propeller flicker (10 FPS). They state that none of the lights provoked seizure, syncope, nystagmus or photic driving. Seven subjects were irritated by the strobe light. This was accompanied by paced alpha rhythm and pulsating pupils. Three subjects were made drowsy by the Grimes light; six by the propeller flicker. The most common complaint was annoyance.

Bynum and Stern (1969) painted the main rotor blades of UH-1 helicopters to determine the possibility of flicker-induced vertigo resulting from viewing the blades from another helicopter in the same formation. In two experiments involving 38 subjects, neither subjective or physiological effects were found.

Again turning to the Melton report, it concludes that the "literature seems to establish that only peculiarly susceptible individuals are seriously affected by intermittent light."

The low incidence of such individuals in the population is offered as the probable chief reason why "no accidents in flight have ever been attributed to flashing lights". Melton suggests that the number of light sensitive people in the population is between 0.01 to 6 percent. This translates to between 50 and 30,000 of the 500,000 pilots in the United States. Through 1963, 113 pilots had been medically grounded by reason of epilepsy. Melton estimates that about 5 percent of these, that is 6 of the 113 could have been photically sensitive.

From these reports, one may conclude that flashing lights similar to those tested are irritating to substantial numbers of crewmen. However, even though seizures of the type mentioned by Berry and Eastwood are quite real, they do not occur often enough to be of major concern. And, finally, crewmen in an adjacent station are not likely to be affected by flicker effects from a sister ship.

#### Cockpit and Compartment Temperature, Ventilation, and Fumes

One of the most prevalent complaints voiced by pilots and crewmembers assigned to helicopters is the high ambient temperatures experienced, along with the lack of adequate ventilation. Temperatures in the UH-2A measured from 6 degrees F to 10 degrees F higher than that outside (82 degrees F) under "doors on - windows closed - vent open" conditions (Bass, 1964). On the ground and in hover the temperature was 88 degrees F; in-flight it measured 90 degrees F. These levels do not appear to be unusually high for helicopters. The small, large bubble types are said to be even hotter because of their large window areas.

In his analysis of fixed-wing Mohawk aircraft missions, Joy (1967) found aircrew discomfort and dehydration as well as accompanying fatigue. He concluded that these problems could be considerably alleviated by drinking water in-flight and by improved cockpit ventilation and clothing ensembles.

Although it is sometimes difficult to attribute a specific impairment of performance to high ambient temperature conditions, heat seems to produce effects in a manner analogous to those caused by fatigue. It has been found in fatigue studies that detrimental effects are more likely to occur if the event rate (in a vigilance task, for example) is high and the task demands continuous attention. Colquhoun (1969) suggests in

his study on vigilance and ambient temperatures, that adverse performance effects would probably have manifested themselves if the event rate were 60 per minute.

Both Air Force Design Handbook, AFSC DH 1-6, and Woodson and Conover (1966) state that physical fatigue begins at 75 degrees F. Further, mental activities slow down and performance errors begin at about 85 degrees F. The effects are, of course, aggravated in humidities beyond the comfortable 30 to 70 percent range.

Cockpit fumes are sometimes complained of by crewmen, particularly by those required to fire machine guns from within a poorly ventilated compartment. In discussions with sonarmen we were advised that the SH-3D has exhaust vents located above and forward of the side door. Not only is the door loosely fitted and prone to vibrate; it also frequently admits engine exhaust fumes, even though fully closed.

Hody and Bailey (1968) investigated weapon exhaust contaminants inside Army helicopters. Although they were unable to identify a clear and present danger, they did find the job of measurement to be quite difficult. They imply that more refined techniques are required to verify their initial results.

#### Disorientation, Vertigo, and Night Lighting

These topics constitute another significant problem area for helicopter pilots. Although our emphasis and scope do not permit in-depth treatment of such important tangential issues, we cite them to underscore the multiplicity of constraints, demands, and difficulties impinging on helicopter crewmen. Most studies on vibration effects fail to consider the combined impact of even a few such factors. Those studies which do include complex elements lead one to conclude that detrimental performance effects increase as a function of the overall difficulty of tasks and adverse environmental conditions.

More specifically in point, disorientation and vertigo are most likely to occur during marginal weather flights and at night. The threat posed by these malefactors can probably be minimized by the use of electronic displays. Vertical Situation Displays (VSDs), for example, provide both a comparatively large attitude reference and easy-to-follow vertical orientation cues (Ketchel and Jenney, 1968). However, the trend toward using such devices imposes an even greater

need to regulate interior cockpit lighting. "Hot spots" must be avoided and the overall lighting intensity must not interfere unduly with external visual tasks.

Red versus white lighting and instrument panel lighting are problems having long histories in military aviation, and it is recommended that a systematic investigation of such topics be subsumed under a broad simulation study program. The many facets of concern include such considerations as dark adaptation, target acquisition using optical or electronic devices, weapon delivery, windscreen light transmission, and interior canopy reflections.

#### Information Display and Management

Our final subject in this section continues the thought introduced above. A broad simulation study program is needed to investigate the use of electronic and optically generated display devices within the helicopter environment. Such devices include helmet mounted, optical tracking, target acquisition, station keeping, navigational, hover, and LLLTV displays. In particular, the IHAS vertical situation display should be investigated under multi-axis vibration conditions for both day and night missions.

A general simulation study program should be supported with adequate task analysis data and with the in-flight recorded vibration data mentioned earlier. One of its purposes would be to produce guidance on electronic display characteristics. Scale factors, data rates, and display dynamics are worthy topics which have not yet been studied in vibration laboratories.

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13. ABSTRACT		
<p>Identifiable vibration characteristics of contemporary military helicopters are described. These provide a basis for analyzing and interpreting the literature on vibration research. Emphasis is given to experimental results which relate to frequencies and acceleration amplitudes falling within the helicopter main rotor effects region.</p> <p>The spectrum of military helicopters is tabulated briefly and six representative Navy/Marine Corps helicopters, missions and associated flightcrew tasks are described in more detail.</p> <p>Perceptual-motor behaviors comprising crew tasks in the six missions are identified. These are used to relate vibration analysis results to the helicopter situation. Qualitative estimates of the susceptibility of present and future mission tasks to the helicopter vibration regime are made.</p> <p>Helicopter flight equipment items such as seats, helmets, helmet-mounted displays, and various other sophisticated electronic devices are analyzed to assess their relevance to crew vibration performance. Duration of exposure, temperature, ventilation, fatigue, and other factors are discussed as they operate in concert with vibration to degrade helicopter flight crew performance.</p> <p>Generalizations are drawn from the research literature and conclusions and recommendations are presented in the areas of: physiological effects, performance effects, subjective tolerance data, on-board crew equipment, integrated displays, vibration isolation and absorption techniques, medical and accident record keeping, design specifications and standards, and additional research requirements.</p>		

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