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UNITED STATES ARMY
TRAINING AND DOCTRINE COMMAND

UNITED STATES ARMY MATERIEL COMMAND

LIGHT HELICOPTER FAMILY
TRADE-OFF ANALYSIS

APPENDIX R

VOLUME VII

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Threat
Analysis
Management
Terrain
Integrated
Integrate
Integration
Intelligence
HMD
FOV
LHX
TOA
ARTI
Simulations
Single-Pilot
Overload
Artificial
(Cont'd on reverse.)
HF/MMI
Helmet
Voice
VCASS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The HF/MMI analysis portion of the Light Helicopter Family (LHX) Trade-Off Analysis (TOA) found/concluded: (1) A fully automated LHX can be operated by a two-member crew without crew overload; (2) A fully automated LHX cannot be operated by a one-member crew without crew overloads during critical mission segments such as air-to-air combat and reconnaissance; (3) Operational analysis indicates the two-crew LHX would be more survivable, more effective, and safer to fly. It also significantly reduces program risk; (Continued on reverse.)

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ITEM 20 (Cont'd):

(4) Automation will be necessary in either a one- or two-crewmember aircraft. The following automation functions are particularly important for a single-crewmember LHX:

Voice Interactive Systems
Automatic navigation
Automatic threat analysis
Automatic threat management
Artificial intelligence concepts
Integrated fire and flight control
Integrated flight engine control
Integrated flight path control
Wide FOV helmet-mounted display
Automatic target detection, acquisition, tracking, and recognition
Terrain following/terrain avoidance (TF/TA)

(5) The initial LHX design should include two crewmembers until critical technologies are sufficiently mature and results from ARTI and governemnt crew-size simulations can validate the single-pilot goal.

Thirteen subanalyses were performed and reported in Annexes found within this HF/MMI volume. Their titles follow and are fairly descriptive of both the sub-study's emphasis and contents: (1) "Projective Application of the Subjective Workload Assessment Technique to Advanced Helicopter Crew System Designs"; (2) "Human Factors Engineering Review of the Integrated Crewstation for the LHX"; (3) "Tactical Implications of One-Man Versus Two-Man Aircrews for the LHX"; (4) "A Computer Analysis to Predict Crew Workload During LHX Scout-Attack Missions"; (5) "Visually Coupled Airborne Systems Simulator (VCASS) LHX Cockpit Simulation"; (6) "Human Factors Assessment of Voice Technology for the LHX Cockpit Simulation"; (7) "Issues for a Trade-Off Analysis of Conventional Versus Advanced Cockpit Controllers for the LHX"; (8) "Biomedical Analysis of Visual Displays and Cockpit Design Options for the LHX"; (9) "NBC Contamination Protection, Detection, and Decontamination Concepts Analysis for the LHX"; (10) "Human Factors Engineering Assessment of Navigation Systems for the LHX"; (11) "The Integration of Voice and Visual Displays for Aviation Systems"; (12) "Theory and Measurement of Human Workload"; (13) "Pilot Workload, Performance, and Aircraft Control Automation".

ITEM 19 (Cont'd):

Workload
Crewstation
One-Man
Two-Man
Simulate
Simulation
Cockpit
Interactive
Display
Displays
Visual
NBC
Contamination
Nuclear
Decontamination
Biological
Chemical
System
Systems
Human
Aircraft
Helicopter
Tilt rotor

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LIGHT HELICOPTER FAMILY TRADE-OFF ANALYSIS

APPENDIX R

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NOTICES (U)

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LIGHT HELICOPTER FAMILY
TRADE-OFF ANALYSIS
(LHX TOA)

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APPENDIX R

HUMAN FACTORS/MAN-MACHINE INTERFACE (HF/MMI) ANALYSIS (U)

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GLOSSARY (U)

A-A	air-to-air
abort	The loss of a mission essential function from the beginning of preflight to complete system shutdown, if essential to completing the specific mission at hand, is considered to constitute a mission abort.
AD	air defense
AFCS	automatic flight control system
AH	attack helicopter
AI	artificial intelligence
ATA	air-to-air
FACTS	FLIR-augmented Cobra TOW sight
GPS	global positioning system
HEL	Human Engineering Laboratory
LCC	life cycle costs
LOA	letter of agreement
MEP	mission equipment package
MFD	multifunction display
MFPK	multifunction programable keyboard
MMWR	millimeter wave radar
MP	mission profile
NOE	nap of the earth
NVG	night vision goggle
OBOGS	onboard oxygen generating system
P^3I	preplanned product improvement
VCASS	virtual cockpit airborne system simulator

VHSIC	very high speed integrated circuit
wpns	weapons

APPENDIX R

HUMAN FACTORS/MAN-MACHINE INTERFACE (HF/MMI) ANALYSIS (U)

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APPENDIX R

HUMAN FACTORS/MAN-MACHINE INTERFACE (HF/MMI) ANALYSIS (U)

R-1. (U) PURPOSE. The intent of this appendix is to assess the human factors/man-machine interface (HF/MMI) associated with the design of the Light Helicopter Family (LHX) of aircraft, to identify the HF/MMI concerns, and to provide recommendations related to crewstation design.

R-2. (U) BACKGROUND.

a. (U) The role of the helicopter in military operations has been greatly expanded in recent years. Helicopters now contribute enormously to the Army's ability to conduct its land combat operations. The helicopter's recently adopted primary role as an antiarmor weapon system means that scout and attack helicopters must be able to fly and complete combat missions day and night in all kinds of weather.

b. (U) The scout and attack (SCAT) mission is a good example of what is expected for the Army's projected single-pilot helicopters of the future (figure R-1): the pilot will have to reconnoiter and contact enemy elements, hand-off targets to other scout/attack elements, help select firing positions, and engage enemy targets. In order to perform these roles, he will have to supervise or control:

-- The data management and transfer system.

-- The flight control, navigation, guidance, and communication systems.

-- The target acquisition and designation systems.

-- The weapon systems.

-- The threat identification systems.

-- The electronic countermeasures (ECM) systems.

The aircrew will more than likely have to do all these things under the stressful and fatiguing conditions of low-level or nap-of-the-earth (NOE) flight in all kinds of weather while avoiding obstacles and probably taking enemy fire.

c. (U) There is growing concern about the effectiveness with which the pilot can perform all the mission tasks expected of him. As the missions and the aircraft become more and more complicated, there is a commensurate increase in demand on the aircrew's time and attention. The response of aircraft cockpit designers to increased workload is usually one of providing

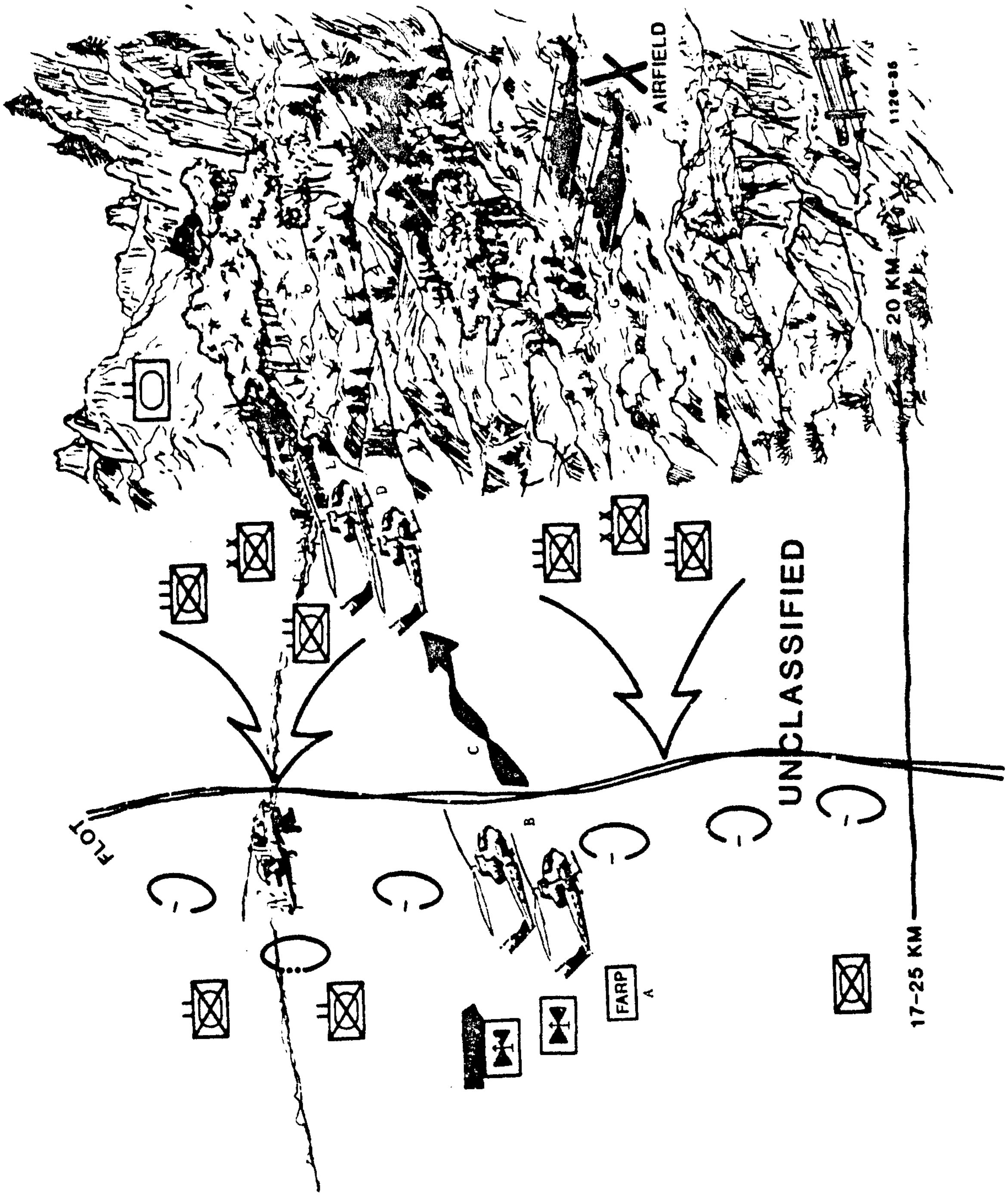

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Figure R-1. (U) The scout/attack mission.

more and more information through the media of advanced displays and devices in an effort to keep the pilot's workload manageable. Aircraft designed to operate near the limits of their performance envelopes and the ready availability of new information display technology make this a necessary and appropriate response. There is a constant danger, however, of going so far in providing additional information that the pilot's cognitive and information-processing capabilities may be exceeded. Given the stress of combat, either near the surface or at altitude, will the pilot be helped by these flight aids or will he be overwhelmed with more information than he can handle?

d. (U) Conventional helicopters already present the pilot with an array of dials, controls, gages, and switches. In the proposed all-electronic crewstation of the LHX, those conventional controls and displays are expected to be replaced with multifunction television-like displays that will have the same type information condensed into a smaller area. The three flight controls found in current aircraft may be combined into a single control operated by one hand. The concentration of displayed information and control functions is expected to place an increasingly greater burden on the pilot's mental capabilities. Increased equipment complexity, along with increased mission complexity, will be accompanied by proportionate increases in the amount of information that will have to be furnished to the pilot. The result of increasing the information available to the pilot may only shift the aviator's effort from manual workload to a workload which is more cognitive in nature.

e. (U) The pilots of the Army's new helicopters will need all the help the avionic systems designer can provide them if they are to execute the missions envisioned for Army 21 battlefields, especially if single-pilot designs are produced. The problem is one of giving the pilot the information he needs at a rate at which he can assimilate it properly and use it effectively.

f. (U) Technological advances in the past two decades have made possible the development of more highly advanced and capable aircraft that can fly under more difficult conditions, at faster speeds, and with much greater agility. At the same time and perhaps as a consequence of these technological advances, the environment in which aircraft must fly and fight has become more dangerous. The only element that has not changed significantly over the years is the human operator. The pilot is limited in his ability to assimilate and perform tasks. He may not be able to fully handle the increased workload involved in operating today's faster, more highly mechanized aircraft. Limitations in human capabilities are difficult to overcome and, as yet, have not been completely described. However, the proper use of automation in aircraft could help to overcome some limitations.

g. (U) If the LHX is to be effective on the intense and dynamic battlefield of the future, the human element must be considered in the crewstation design and system integration early in the concept formulation process. The HF/MMI substudy of the Trade-Off Analysis (TOA) is directed toward the assessment of the HF/MMI issues associated with the LHX from the user's perspective.

R-3. (U) ASSUMPTIONS.

a. (U) The goal of the substudy was the identification and assessment of HF/MMI concerns. The HF/MMI substudy, in the limited time available, would not be able to determine and/or recommend solutions to all the issues. Therefore, the HF/MMI substudy would concentrate on cockpit configuration and crew size.

b. (U) The LHX-Utility would be designed with a two-man cockpit (one-man operable) for passenger safety.

c. (U) This analysis would be limited to the LHX-SCAT aircraft.

R-4. (U) LIMITATIONS.

a. (U) The primary limitation was that of time and facilities available to conduct human factors research assessments and analysis.

b. (U) The proposed mission equipment for the LHX is unavailable for testing; thus, the data used is restricted to projections of the capabilities and limitations of the proposed mission equipment package (MEP).

R-5. (U) METHODOLOGY. The United States Army Aviation Center's LHX HF/MMI analysis used the Trade-Off Determination (TOD) as a baseline. The TOD reports were supplemented by additional analyses. Also, additional data was obtained through an information search, specific inputs of subject matter experts, an expanded mission task analysis, pilot interviews, the application of a subjective work load assessment, and limited engineering simulations.

a. (U) The information search was used to obtain data on current and future technologies, cockpit designs, and cockpit integration programs. Data was reviewed for both the helicopter and fixed wing aircraft. The study team solicited the assistance from numerous laboratories throughout the defense establishment to contribute their technical expertise in the conduct of the analysis. The technical literature was reviewed for relevant LHX studies, assessments, and data. That information, coupled with ongoing aviation research programs, was evaluated in light of LHX missions and constraints. Air Force and Navy programs were also reviewed. Programs reviewed included the Advanced Flight Technology Integration (AFTI)/F-16 program, the Cockpit Automation Technology (CAT) program, the F-15 dual role fighter (DRF), and the F/A-18 program.

b. (U) The Air Force Aeromedical Research Laboratory (AFAMRL) developed subjective workload assessment technique (SWAT) was applied in the evaluation of five conceptual crewstations for the LHX-SCAT. Each concept, based on a distinct level of a wide field of view (WFOV) display technology, was assessed by a team of Army aviators with varied aircraft expertise and backgrounds in the scout and attack missions. The MEP analyzed was that projected for the LHX-SCAT. A composite mission scenario was synthesized and six mission segments were used to collect workload estimates.

c. (U) The mission task/workload analysis, started during the TOD, was expanded during the TOA to cover the MEP alternatives for both the one- and two-man cockpits. Additional analyses were conducted to determine the expected workload levels provided by the MEP as described in the earlier draft LHX Required Operational Capability (ROC) documents.

d. (U) Operational pilots were utilized in limited engineering simulation which investigated the man-machine interface concerns for the single-pilot attack helicopter mission. The exploratory simulation program, using the virtual cockpit airborne system simulator (VCASS) at Wright Patterson Air Force Base (AFB), constituted the first engineering-type simulation to assess proposed LHX mission equipment and HF/MMI concerns. During that limited simulation effort, LHX-type mission segments were flown in a crewstation that contained controls and displays similar to those expected in the LHX. The major area of concern during the simulation was target acquisition and engagement by means of a helmet-mounted display (HMD) system.

e. (U) Structured interviews were conducted with operational pilots from the Army, Navy, Air Force, and Marine Corps. The study team interviewed Army pilots from a number of units and locations. Navy pilots were interviewed at Lemore Naval Air Station (NAS), California. Air Force pilots included instructor pilots from Williams AFB, operational pilots from the F-15 Wing at Eglin AFB, and operational A-10 pilots on temporary duty to Fort Rucker, Alabama. In addition, Army and Marine Corps pilots from the air-to-air training detachment at Yuma, Arizona, were interviewed.

f. (U) The information and data obtained from the above sources were used to provide an analysis of the crewstation configuration proposed for the LHX, the technologies and mission equipment expected in the LHX, crew workload, and a crew complement assessment. The results of that analysis are summarized in the following paragraphs of this section. More detailed coverage of specific critical areas, provided by subject matter experts in each of those areas, can be found in annexes I through XIII of appendix R.

R-6. (U) RESULTS OF ANALYSIS.

a. (U) General. The LHX program is dynamic in nature and new information is available on an almost continuous basis. The HF/MMI assessment for the LHX must, therefore, be considered an iterative process that should be updated as the emerging results of the Advanced Rotorcraft Technology Integration (ARTI) program, LHX simulation efforts, and other Department of Defense aviation research and development (R&D) programs progress. This analysis is based on the information available during the TOA time frame. Detailed results of the methodology applied to the HF/MMI analysis can be found in the annexes of this report. The following discussion integrates the conclusions and recommendations of those individual reports to provide an overview of the major man-machine interface concerns and issues resulting from the HF/MMI analysis.

b. (U) Mission Task Analysis.

(1) (U) The mission task analysis began with a review of 24 LHX-SCAT mission profiles to determine the critical mission segments that have the greatest impact on aviator workload. Each of the mission profiles were subdivided into mission segments. Twenty-nine segments were then selected for further analysis. These segments were considered representative of the LHX mission activities. Each of the mission segments was then broken down into critical flight control and mission support functions and was positioned on a mission time line. Functional analyses were performed by identifying the critical performance elements with their man-machine interface. Sensory, cognitive, and psychomotor workload and durations were estimated for each performance element.

(2) (U) Computerized one- and two-crewmember models were developed. These mission and function analysis results, including the workload and duration estimates, were used as the data base. Decision rules were written for building functions from the performance elements and mission segments from the functions. The computer models were used to predict total workload in four components: visual, auditory, cognitive, and psychomotor during concurrent performance elements. Performance elements and subsystems associated with excessive workload were identified. The results were used to compare the one- and two-crewmember configurations.

(3) (U) Two computer-aided analyses were completed. The first analysis was completed for the LHX without automation. Data indicated that, for the one-man aircraft, the pilot experienced overloads in all 29 segments analyzed. For the two-man crew aircraft, overloads remained in 15 segments. A second analysis was then completed for the aircraft with full automation. Although no overloads were identified for the two-man crew, overloads remained in two critical segments (air-to-ground target engagement and reconnaissance) for the one-man aircraft.

(4) (U) After establishment of the LHX draft ROC, the one- and two-crewmember workload models were once again exercised in order to estimate the workload reduction that would occur with the automation opportunities provided by the draft ROC. A review of that document revealed that several automation options assumed during the original full-up MEP workload analysis would not be available. A preliminary review of the mission task analysis, using the draft ROC-proposed mission equipment and automation options, indicates that crew overloads will still remain in several critical mission segments and may, in fact, increase. The draft ROC has since been changed to a letter of agreement (LOA). The LOA is currently under revision. The results of the mission task analysis need to be reassessed when the LOA becomes firm.

(5) (U) In summary, the results of the mission task analysis indicate that, with full automation, the single crewmember will experience overloads during critical segments of combat missions. A second crewmember in the cockpit would eliminate those overload conditions. In an LHX with less than full automation, the crew overloads can be expected to increase. The proposed automation in the early draft ROC for the LHX did not include full automation.

c. (U) Subjective Workload Assessment Technique (SWAT).

(1) (U) Technique.

(a) (U) SWAT has been used successfully by the US Air Force in the evaluation of mission equipment and aircrew station design. It allows the experience and knowledge of subject matter experts, in this case operational pilots, to be used in a systematic manner to assist in determining the optimal crew station design. For the LHX, it was applied as a means of evaluating five conceptual crewstation designs and their associated MEP. A composite mission scenario was developed for use during the assessment. Six mission segments (cruise, pre-forward line of own troops (FLOT), FLOT penetration, approach to battle position, air-to-ground target acquisition and engagement, and air-to-air target acquisiton and engagement) were selected as points at which to collect workload estimates.

(b) (U) The crewstation configuration assessed consisted of a fully integrated MEP including multifunction displays, target acquisition and engagement systems, search and acquisition radar, and voice interaction systems. Each of the five crew station configurations was different in that each design was based on a distinct level of field of view (FOV) display technology (figures R-2 through R-6):

1. (U) Heads-up display (HUD) (20° x 30° FOV). Referred to as the "LHX Baseline Configuration" and shown in figure R-2.

2. (U) Monocular helmet-mounted display (HMD) (30° x 40° FOV). Referred to as "LHX Option 1 Configuration" and shown in figure R-3.

3. (U) Binocular HMD medium FOV display (60° x 90° FOV). Referred to as "LHX Option 2 Configuration" and shown in figure R-4.

4. (U) Binocular HMD wide FOV display (60° x 120° FOV). Referred to as "LHX Option 3 Configuration" and shown in figure R-5.

5. (U) Cabin-mounted projection display system (120° x 220° FOV). Referred to as "LHX Option 4 Configuration" and shown in figure R-6.

(c) (U) The workload associated with the baseline display and each of the four options was assessed by 11 Army operational pilots who were experienced in utility, scout, and attack helicopter missions, including the latest advanced attack helicopter (AH-64).

(2) (U) Conclusions. The major conclusions drawn from the application of the SWAT approach to the LHX were:

(a) (U) A wide range in workload may be expected to be encountered during the conduct of the LHX-SCAT missions (figures R-7 through R-12). The exact level of workload that will be experienced may be significantly modified by the crew system interface concept employed by the weapon system. The minimum expected workload level was found for the cruise mission segment,

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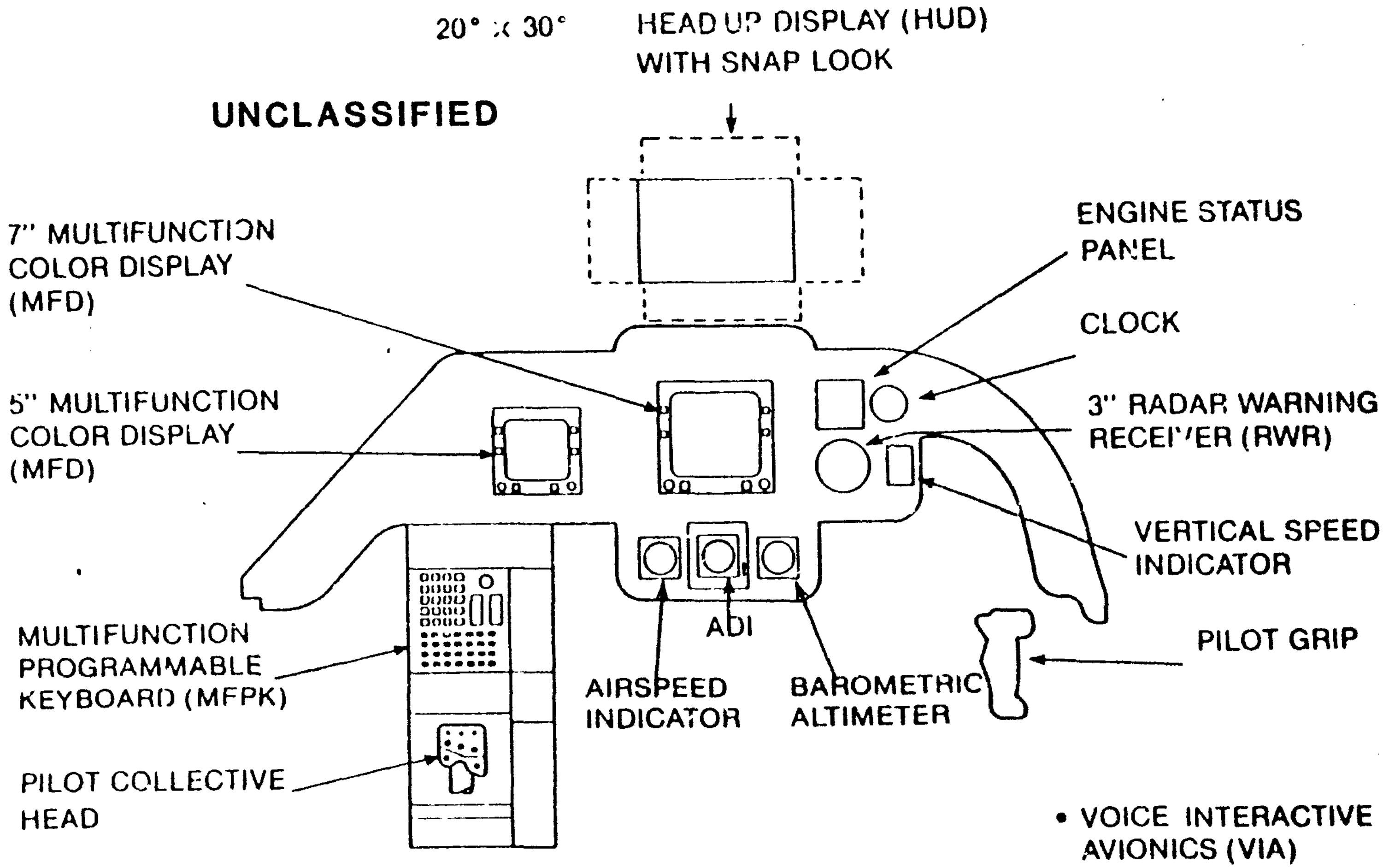

Figure R-2. (U) LHX baseline configuration (20° x 30° FOV).

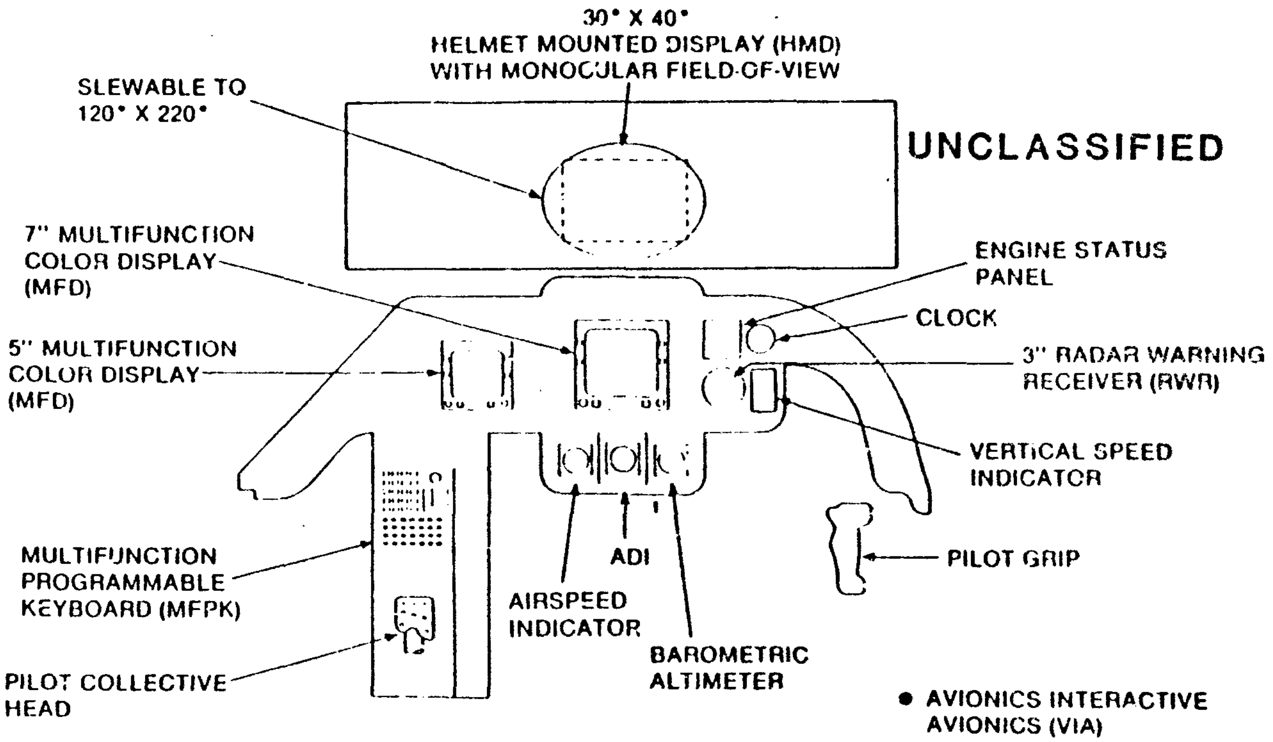

Figure R-3. (U) LHX option 1 configuration (30° x 40° FOV).

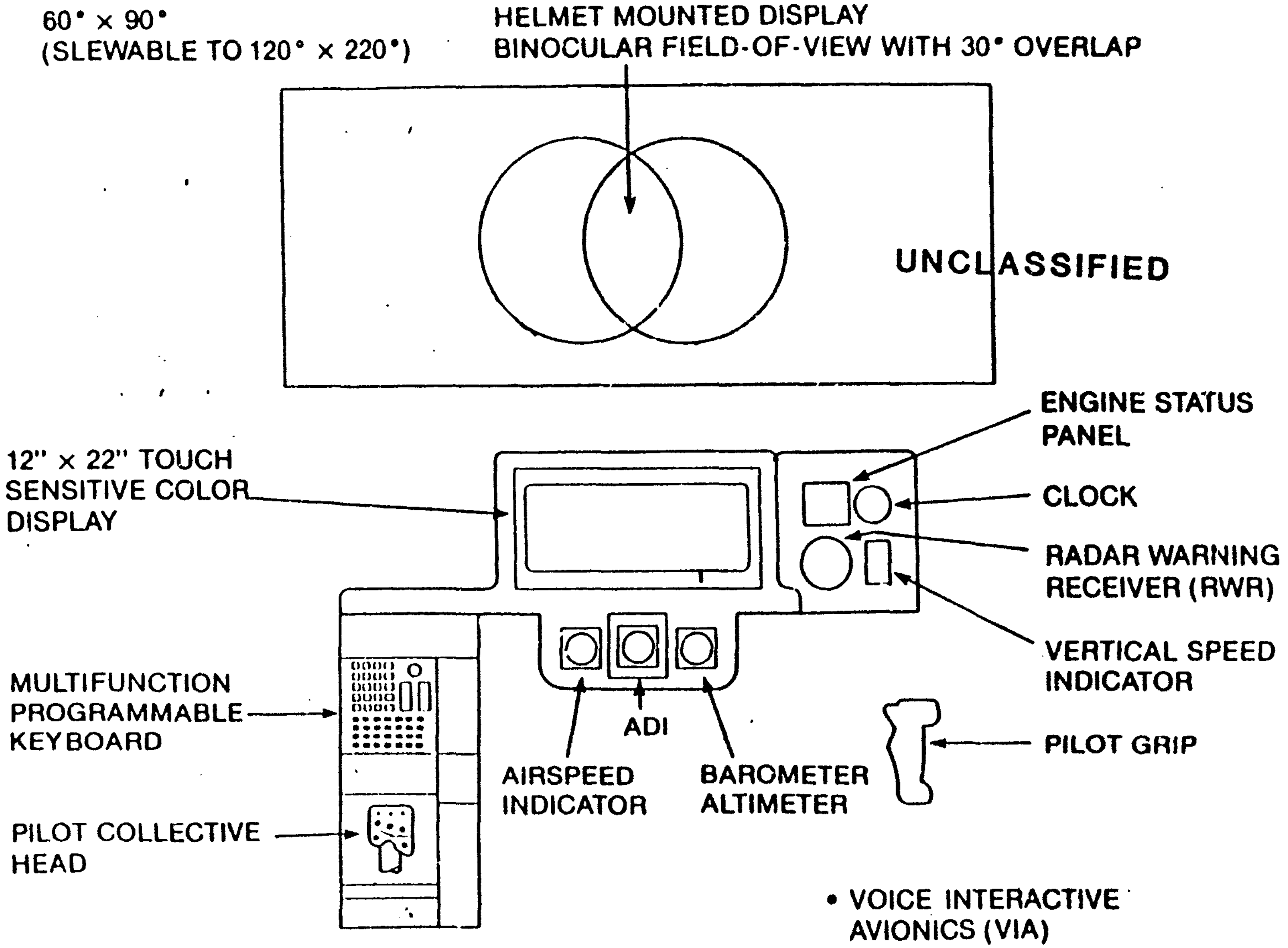

Figure R-4. (U) LHX option 2 configuration (60° x 90° FOV).

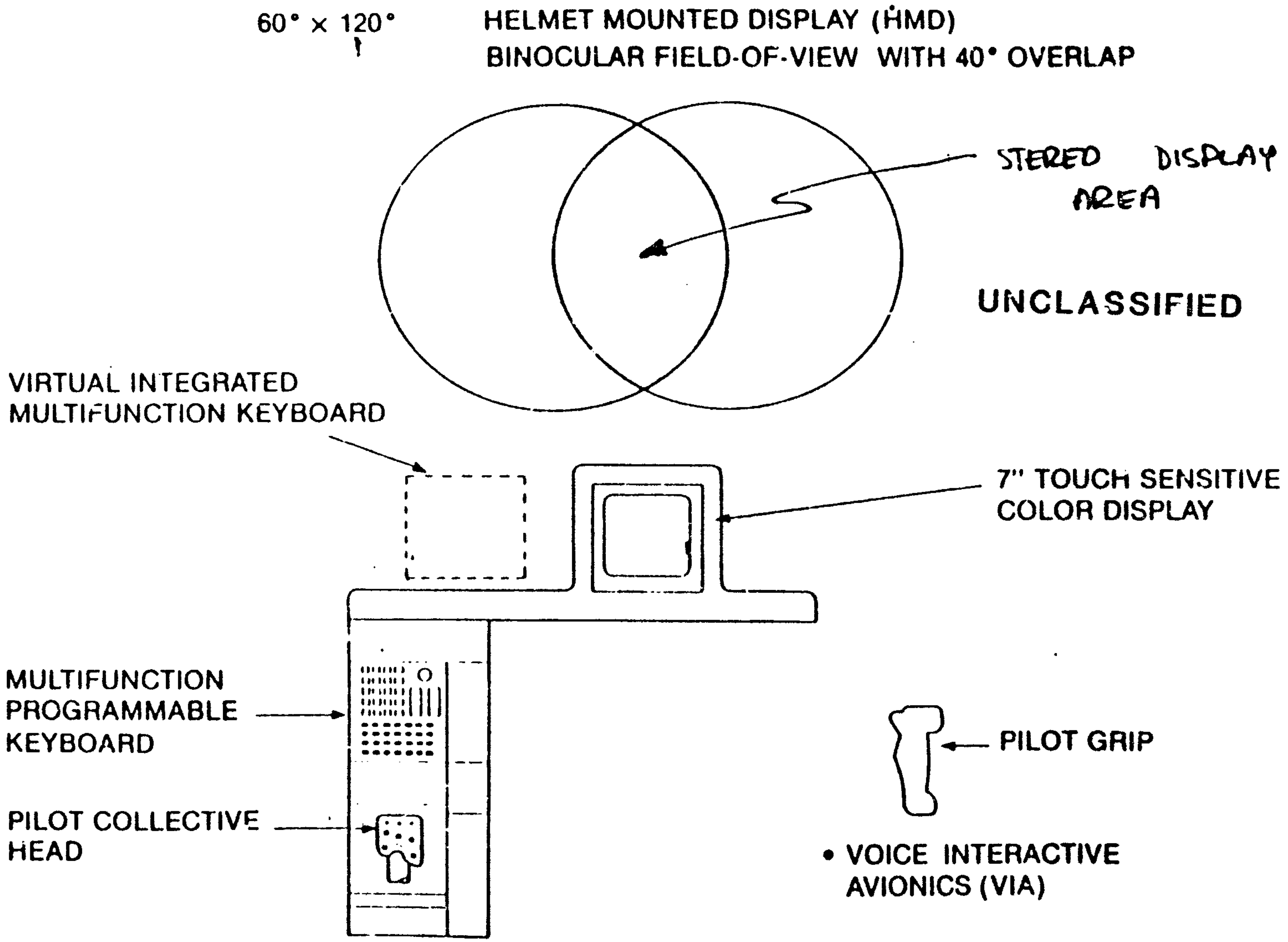

Figure R-5. (U) LHX option 3 configuration (60° x 120° FOV).

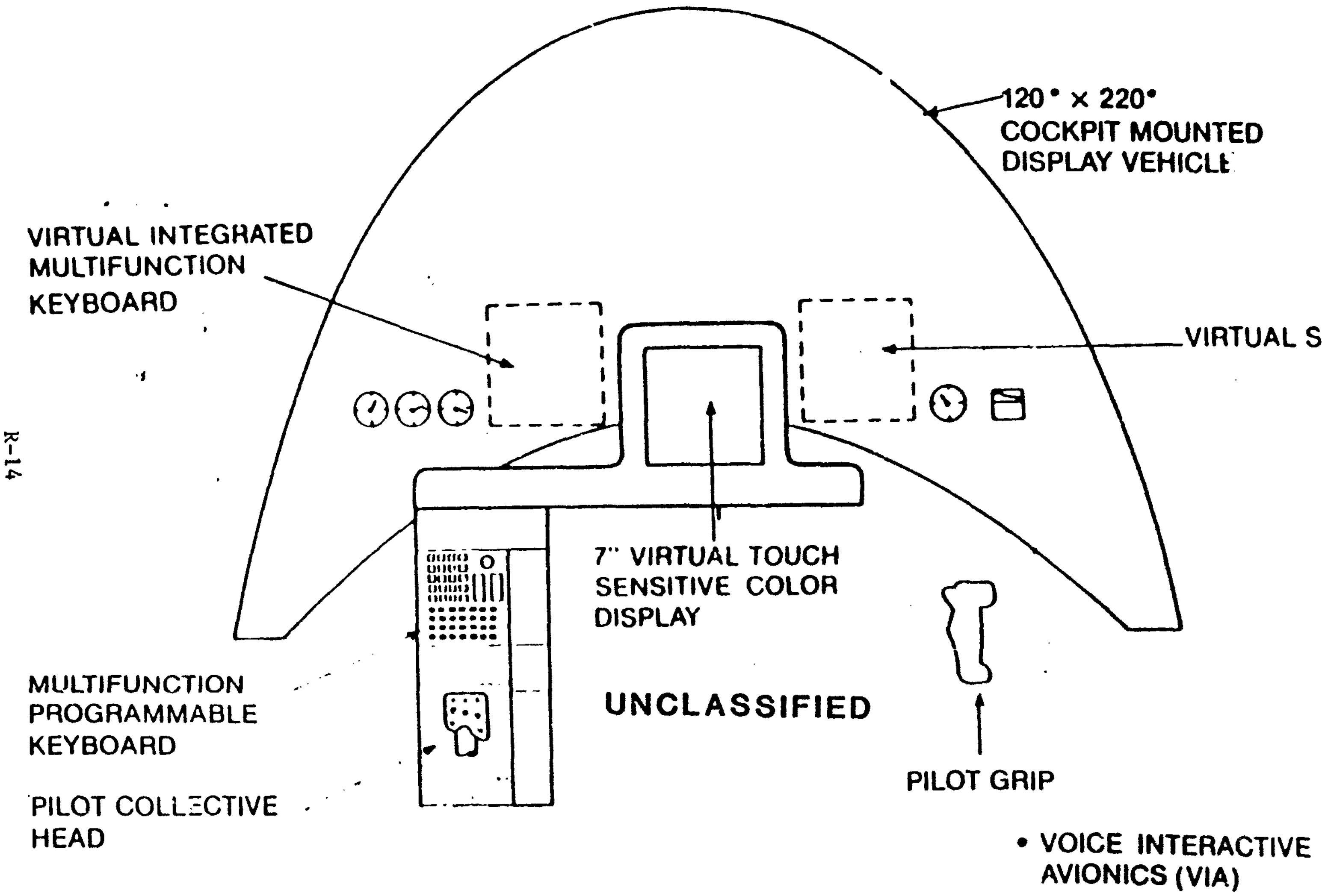

Figure R-6. (U) LHX option 4 configuration (120° x 220° FOV).

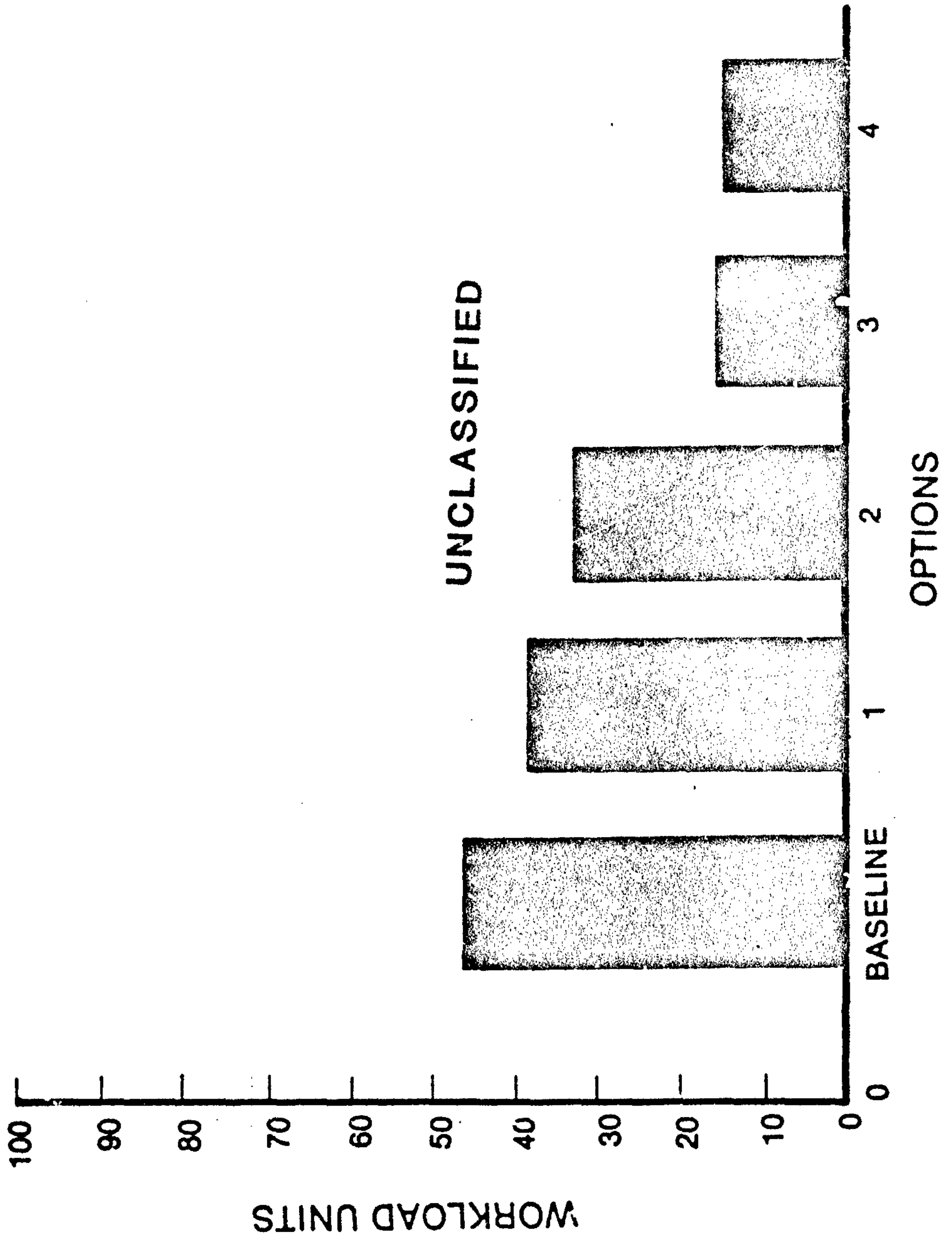

Figure R-7. (U) LHX workload--cruise.

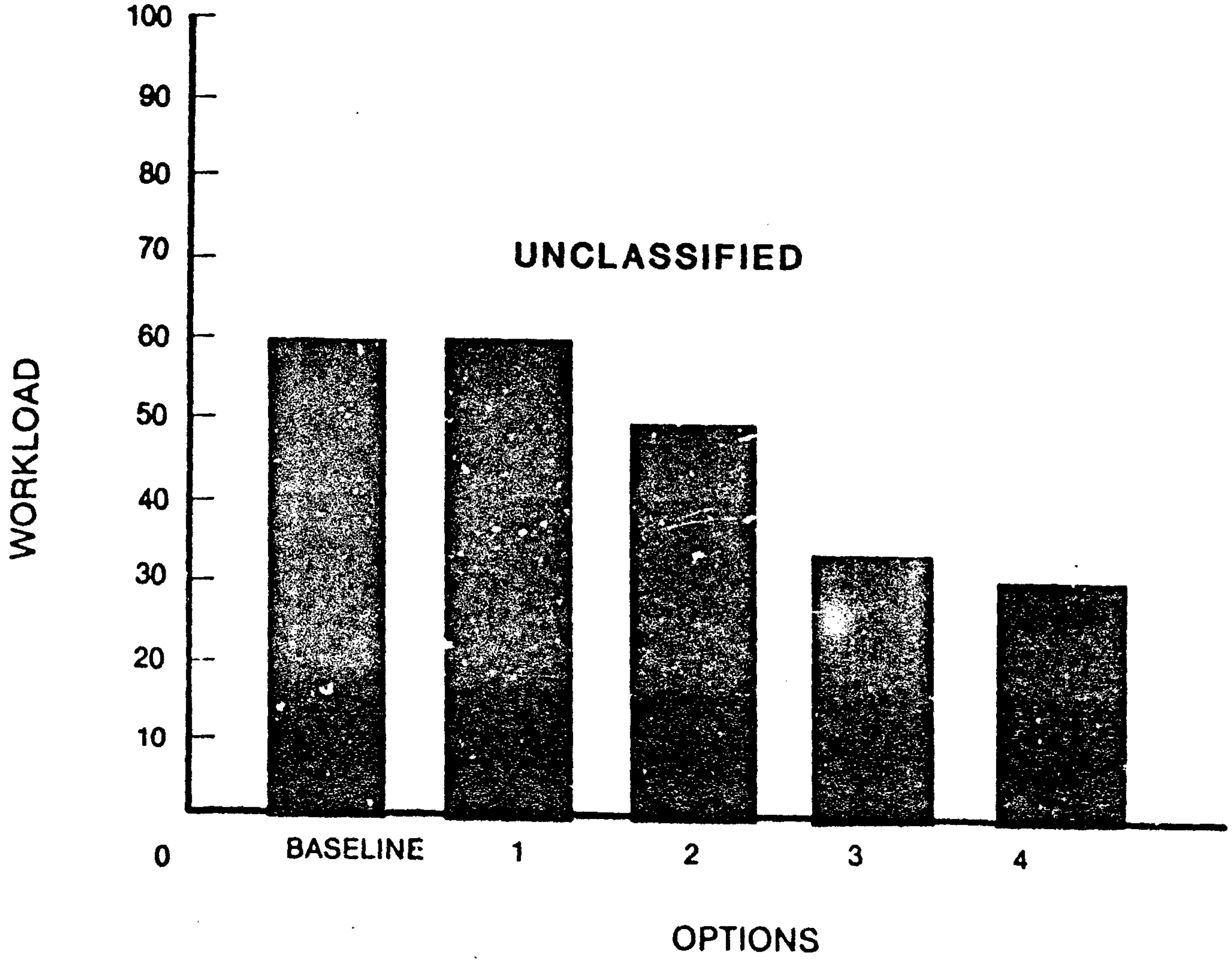

Figure R-8. (U) LHX workload--pre-FLOT.

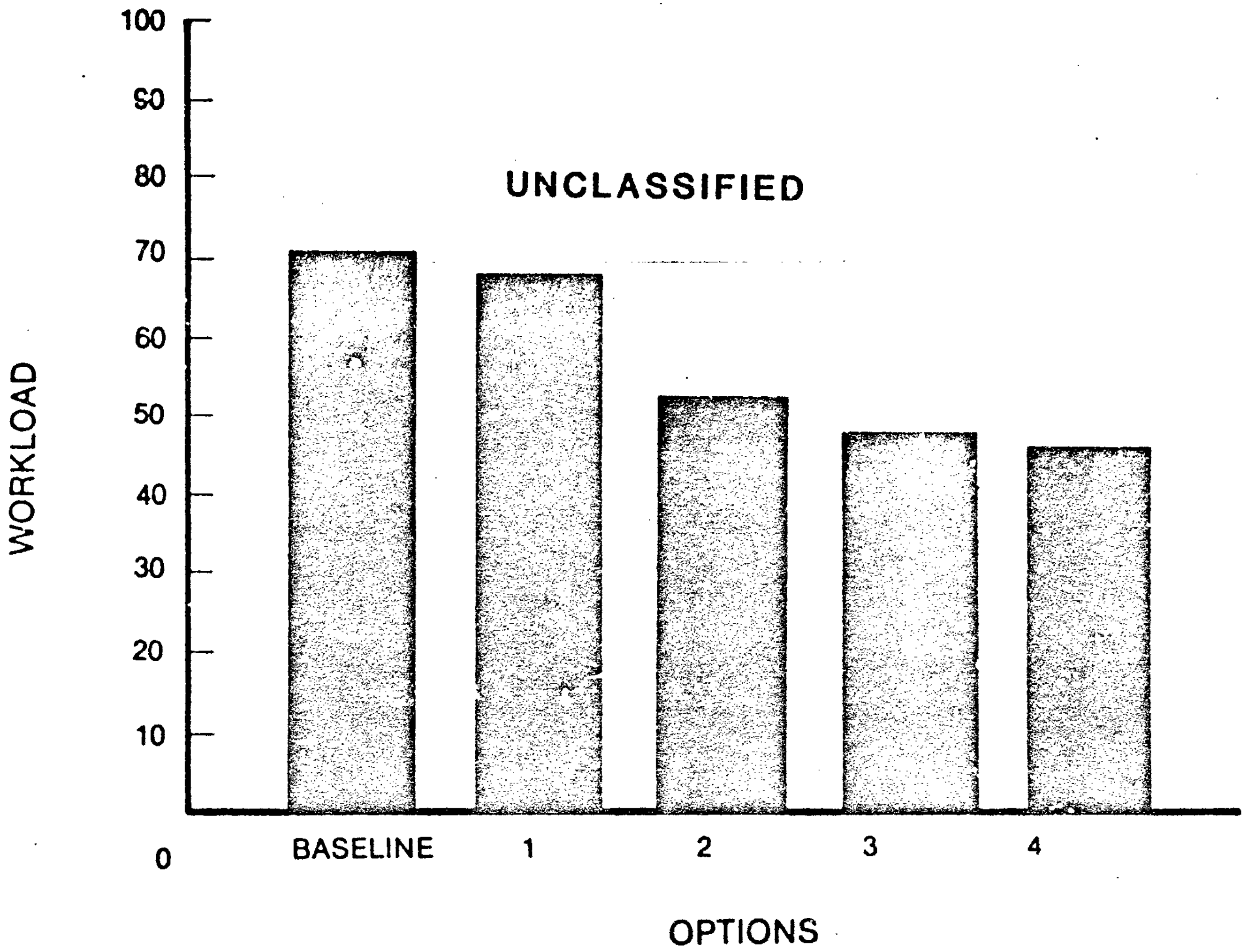

Figure R-9. (U) LHX workload--ingress.

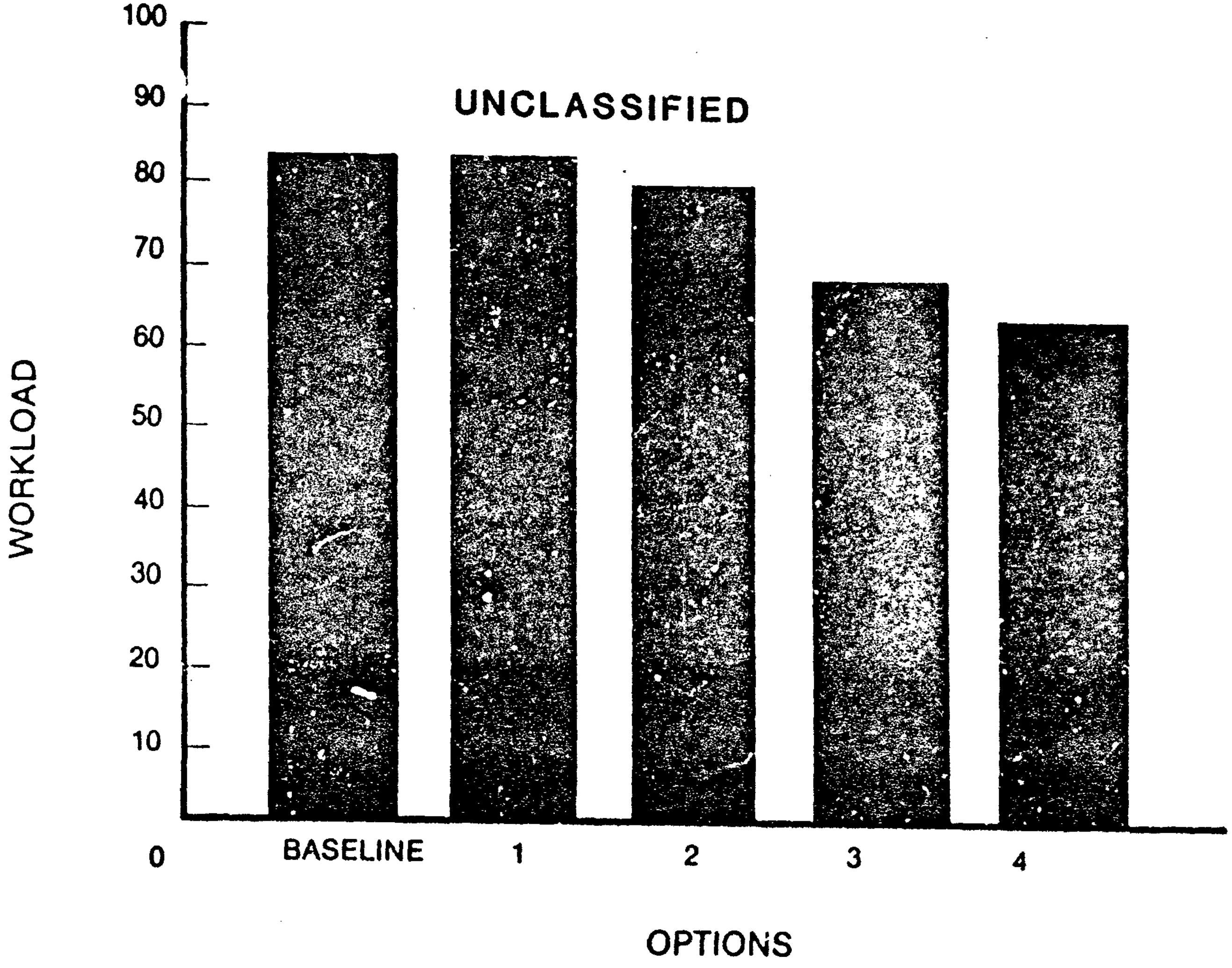

Figure R-10. (U) LHX workload--approach to B.P.

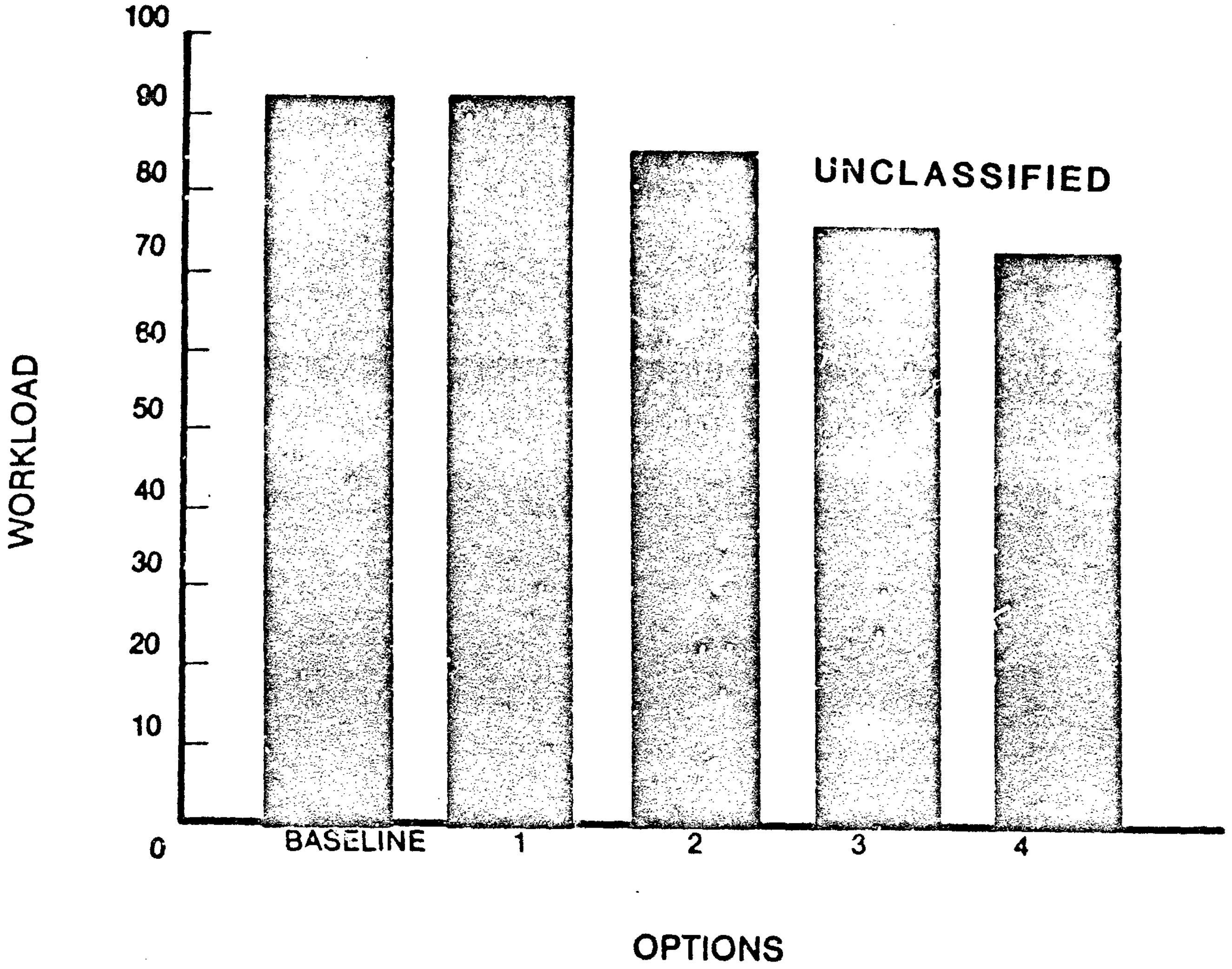

Figure R-11. (U) LHX workload--A/G.

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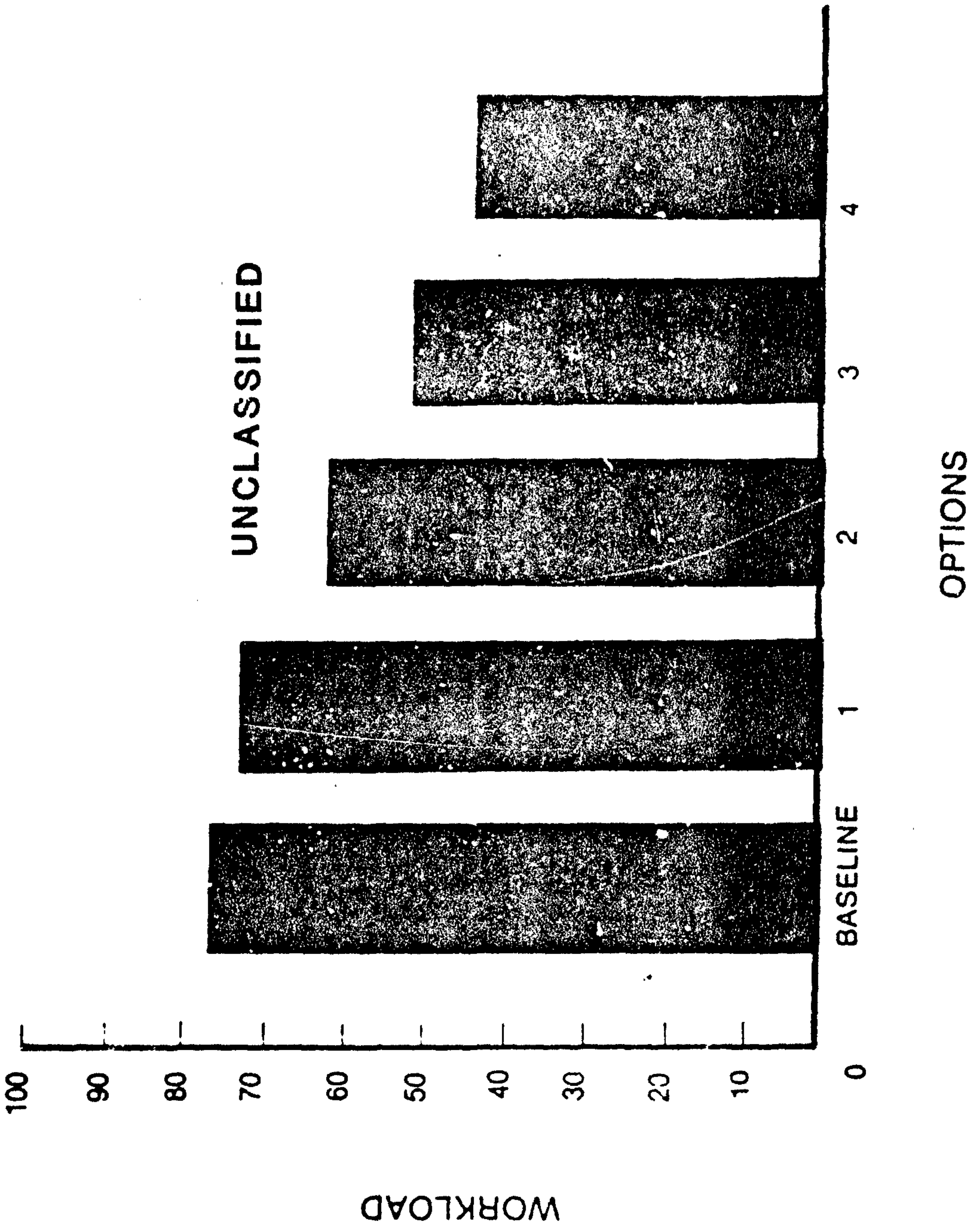


Figure R-12. (U) LHX workload--A/A.

employing option 4 (cockpit-mounted, WFOV, projection display), and the maximum expected workload level was encountered for the air-to-ground attack mission segment using the baseline heads-up display (HUD).

(b) (U) A signficant reduction in workload can be expected with a wide FOV display versus present cockpit designs and narrow FOV monocular displays. Wide FOV display technology is expected to make a considerable contribution to achieving and maintaining good situational awareness, supporting mission effectiveness, and providing required functional support (pilotage, navigation, communication, target acquisition, weapon delivery) and LHX survivability.

(c) (U) Wide FOV HMDs should be considered critical for both one- or two-crew LHX. The crew size of the LHX will determine the FOV required. Although further research is needed, at least a 40° x 120° FOV display is considered essential for effective survivability of the single-pilot LHX.

(d) (U) The LHX display effort should be directed at providing the LHX pilot with the largest FOV possible within the constraints of cost, risk, weight, and sensor and display resolution.

d. (U) Engineering Simulation.

(1) (U) Visually Coupled Airborne System Simulator (VCASS) description.

(a) (U) Engineering simulation was conducted in the VCASS facility developed by the Visual Display Systems Branch of the Human Engineering Division within the AFAMRL at Wright Patterson AFB, Ohio. The VCASS provides a capability to present computer-generated imagery on an HMD to each eye independently. Each ocular of the HMD optics can provide a FOV of up to 60° vertical by 80° horizontal, with up to a 40° overlap between the fields. Thus, the size of the FOV may be manipulated for experimental evaluation. The instantaneous orientation of the oculars (as controlled by head movement) is measured by a magnetic helmet tracker, allowing information displayed on the oculars to be translated relative to head movement so that the displayed images appear to be stable in space. In this way, a panorama of information is available to the operator as a function of head position.

(b) (U) The virtual cockpit, as it was employed in the present simulation, is depicted in figure R-13. Missile selection, electronic countermeasures/aircraft survivability equipment (ECM/ASE) activation, and target designation could all be executed by positioning the "cross hairs" reticle over the intended object. Reticle position is measured by the VCASS helmet-mounted sight (HMS) system and is boresighted by the pilot prior to flight. The virtual cockpit also includes a heading tape and flight director information (altitude, airspeed, missiles, and ECM/ASE status) as shown. The diamond (on the horizontal bar next to the reticle in this picture) provides a steering command, while the adjacent numeric readout provides the flight

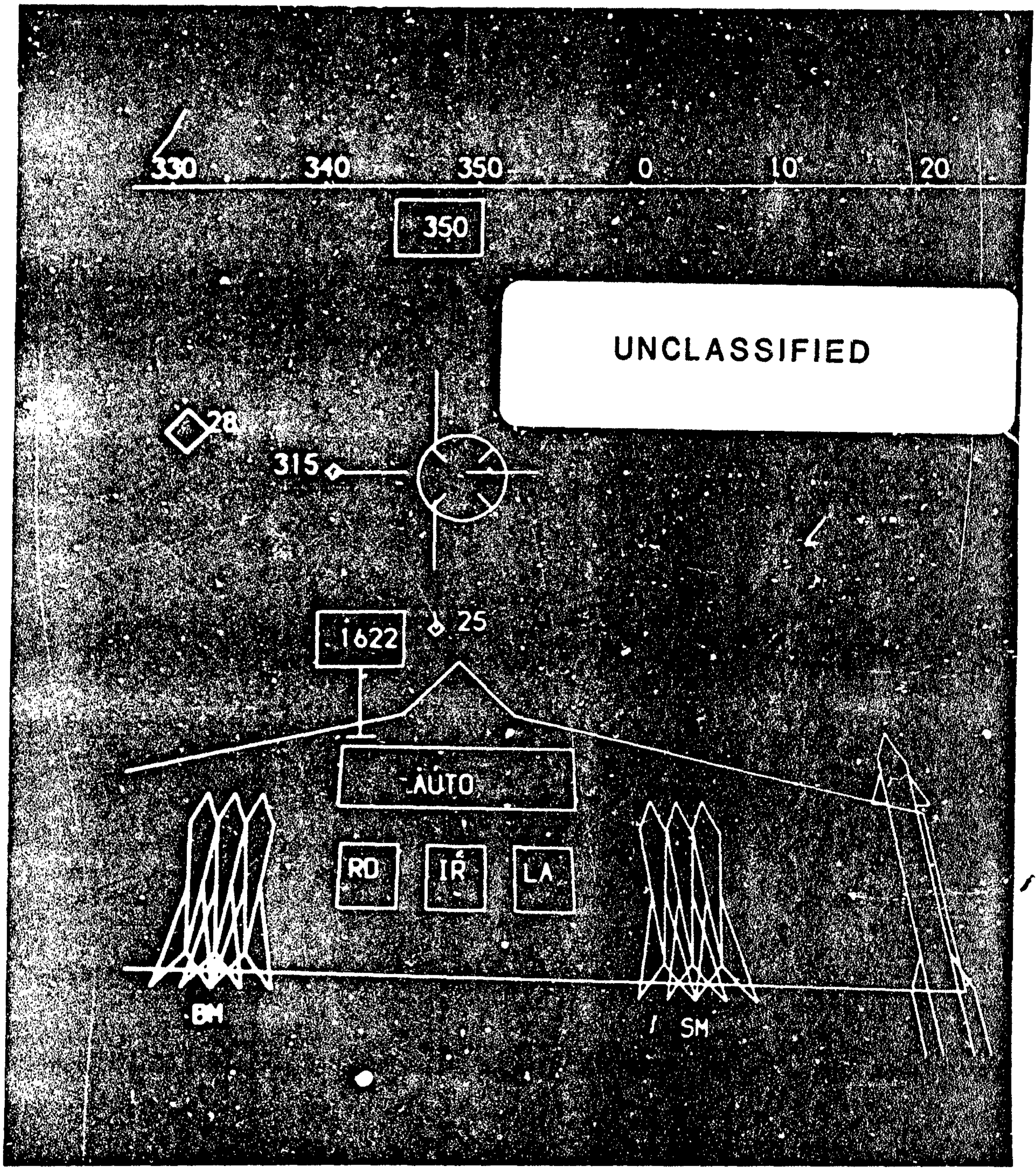


Figure R-13. (U) The virtual cockpit.

vector to the target. Airborne and ground threats are viewable in the out-the-window scene, provided they are close enough and the pilot has them within his FOV. Similarly, tracer rounds from either the LHX or a simulated Soviet HIND helicopter, as well as missile launches and hit bursts, are displayed. Figure R-14 shows the total display concept, which includes both the virtual cockpit and the rudimentary terrain depiction. Solid, dashed, and blanked lines represent ground, marsh, and water features, respectively.

(2) (U) Simulation requirement. The simulation was developed to satisfy a number of requirements. Below is a listing of these requirements, together with an indication of how they were satisfied.

(a) (U) The simulation gaming area was to correspond to a point in the composite mission scenario (Fulda region of Germany) used previously during the SWAT study. The engagement area was selected to be 10 kilometers (km) from the FLOT.

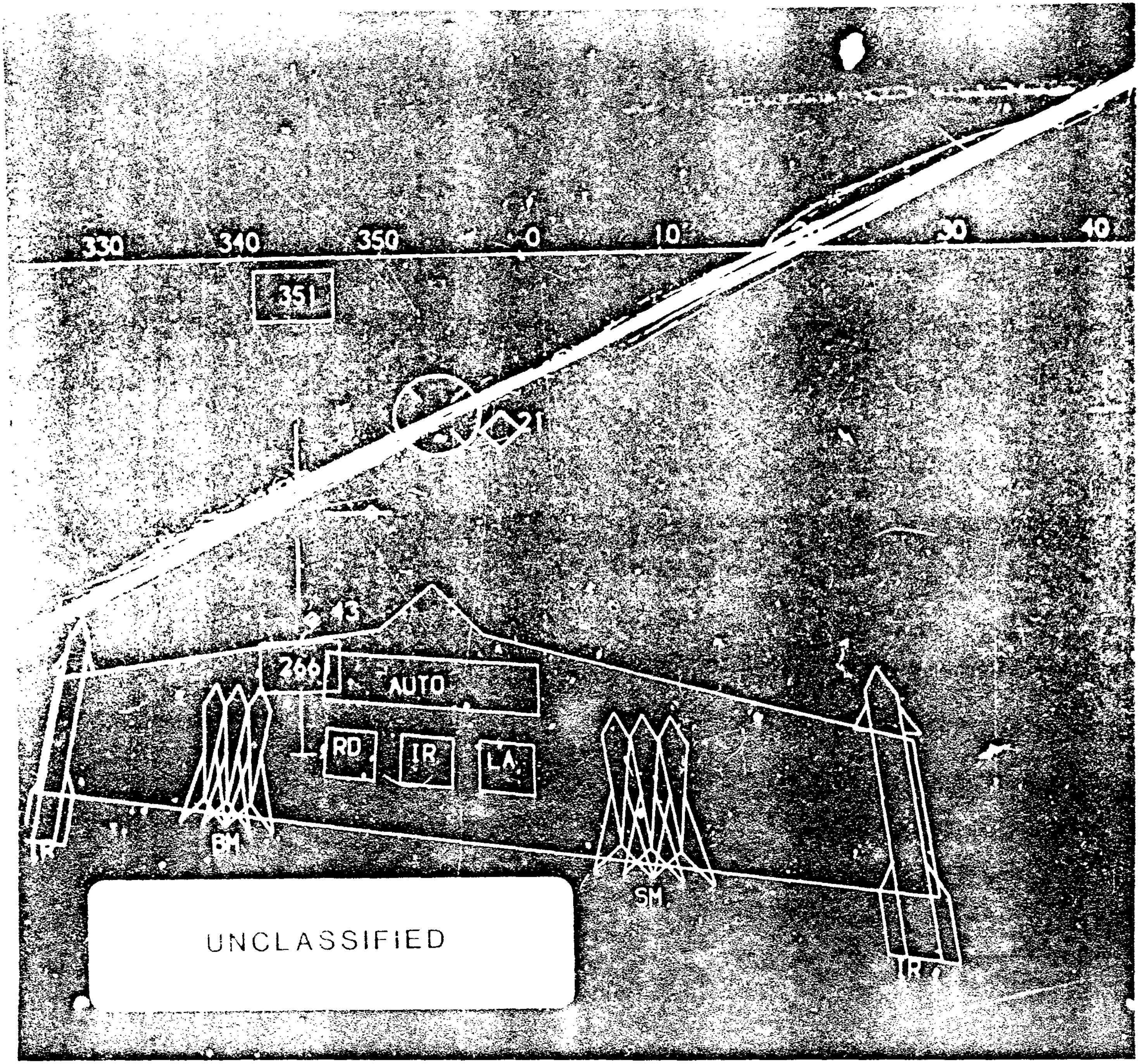
(b) (U) The pilot's task had to be realistic within the mission scenario. (The pilots were tasked to follow the flight director information, which would vector them to the primary targets.)

(c) (U) Other ground and airborne threats were to be encountered on the way to the primary targets. (A simulated HIND helicopter, an antiaircraft artillery (AAA) site, and three surface-to-air missile (SAM) sites were located at random within a 10-km to 20-km radius from the fixed start position. Although the tanks were passive, the other threats were capable of lethal weapon deliveries if the LHX was within their range and not masked by terrain. The HIND, once shot down, was always replaced by another HIND somewhere within the threat area after approximately 5 seconds).

(d) (U) The state of the target acquisition systems associated with each of the threats had to be communicated to the pilot. (Recorded voice announcements were provided to the pilot whenever the LHX was radiated by a threat's emitter and not masked by terrain. Announcements provided target type (i.e., infrared (IR) or radar target), clock position and range information. Threat emitter mode changes (i.e., search, acquisition, tracking, or launch) were signalled to the pilot via a set of threat warning tones.)

(e) (U) A secondary task was provided to ensure the pilots were task-loaded at all times. During that task, the pilots were requested to indicate, via a button on the collective, whether an alphabetic character presented over the headset was or was not one of a previously memorized set of items.

(f) (U) Sufficient LHX armament was to be provided to enable the pilot to knock out the primary target (tank) as well as to deal effectively with the HIND and the AAA and SAM sites. Three guided missiles, three "fire-and-forget" missiles, and a 30-millimeter (mm) cannon with 300 rounds of ammunition were provided.



UNCLASSIFIED

(g) (U) ECM/ASE capabilities were to be provided under pilot control. (Pilots could select IR or radar countermeasures individually or place both in an automatic mode for intervals of 30 seconds each, at which time they were not vulnerable to IR or radar detection by threats.)

(h) (U) Measures of workload resulting from various FOV displays were to be generated by four subject pilots. (Subjective evaluation of workload was provided through a broad range of both structured and unstructured questionnaire responses). In addition, SWAT ratings were obtained on the major mission task elements.

(3) (U) Simulation results.

(a) (U) Field of view.

1. (U) Figure R-15 shows the average of pilot ratings (on a seven-point scale) of the effects of FOV size on overall mission success, as well as on the discrete functions of piloting, navigation, target acquisition, weapon delivery, and survivability. Anchor points were provided at both ends of the scale. A rating of one indicated the probability of success was extremely small, while a rating of seven indicated maximum effectiveness.

UNCLASSIFIED	Horizontal FOV			
	40° Monocular	40° Binocular	90° Binocular	120° Binocular
Overall mission	1.75	2.75	5.0	5.5
Piloting	2.25	3.75	5.7	6.0
Navigation	2.25	3.55	5.5	6.0
Target acquisition	1.75	3.25	4.5	4.75
Weapon delivery	2.75	3.75	5.25	5.0
Survivability	1.5	2.5	5.25	5.75
Situational awareness	1.0	2.5	5.0	5.25
Pilot acceptability	1.25	2.75	5.5	6.0

Figure R-15. (U) Mean of pilot ratings of FOV effects on mission and mission functions.

2. (U) In general, the pilot responses favor a binocular wide FOV in the 90° to 120° range. Both those were rated much higher than the 40° monocular or binocular FOVs. The difference in ratings between the 90° and 120° FOVs was, however, relatively small.

3. (U) The pilots were then tasked to narratively describe the effect FOV was likely to have on a single-pilot's performance for air-to-air, antiarmor, and reconnaissance missions. Their statements indicated that, for the air-to-air mission, a greater FOV should increase the accuracy of and decrease the time required for target acquisition. It was felt that a narrow FOV would limit maneuverability and decrease acquisition capability. A concern was expressed that the high workload resulting with a narrow FOV would adversely affect survivability. All pilots wanted as wide a FOV as possible for overall mission effectiveness.

4. (U) The results of the engineering simulation effort point out the need for a binocular, wide FOV display for the LHX. A minimum horizontal FOV of 90° was indicated and a 120° horizontal FOV was preferred. There also was an indication that the payback in improved mission effectiveness between the 90° and 120° FOVs was less than the improvement obtained between the 40° and 90° FOVs.

(b) (U) Operational concerns.

1. (U) Voice control. During the engineering simulation, a state-of-the-art voice interactive system was used for weapon designation and control. During several engagement tasks, the weapon did not fire when verbally commanded by the pilots. Although this was simulation, it contributed to an immediate increase in pilot stress. This does not mean that voice systems are not viable for the LHX; it simply means that, for voice control of critical systems, it must work the first time and every time because, when it fails, the pilot must use a backup control medium and thus becomes reactionary in trying to complete the follow-on tasks. In addition, based on both prior studies and this simulation, it appears that, depending on types of feedback required, voice command of some functions may take longer than conventional switching.

2. (U) Conventional hands-on switching. Conventional switching, i.e, selecting a radio transmitter by turning a dial on the radio control unit, requires the pilot to divide his attention between inside and outside the cockpit. This is unacceptable while flying as a single pilot at low-level or NOE altitudes. Hands-on switching would allow the pilot to make that same selection by possibly depressing a button on the cyclic or collective. With the optimization of switchology, this will probably be the most viable approach to reducing the amount of time the pilot spends with his head inside the cockpit looking for dials and switches.

3. (U) Degraded mode operations. Many potential problems exist with respect to degraded mode operations. With a single pilot, the mission abort point (in terms of equipment status) will typically occur earlier in the mission than with two crewmembers. While this can be partially compensated for by software reconfiguration, it cannot be completely resolved in this manner. The precise implications of, and compensatory mechanism for, degraded mode operations with a single pilot will require extensive analysis and simulation (including testing to failure) to determine the level of degradation allowed for the single pilot.

4. (U) Off-axis weapon control.

a. (U) This issue revolves around the problem of controlling and firing a weapon system off-axis, while concurrently flying the aircraft and maintaining obstacle clearance. The problem is particularly significant during NOE or low-level, high-speed flight, night, or adverse weather operations. The automation issue is whether the flight control system and/or the weapon system can approach the human capability of the second crewmember. In order to replace the second crewmember during off-axis weapon control, an accurate terrain-following/terrain-avoidance flight control system is required. Such a system has not been demonstrated, and cost and weight considerations might make such a capability (if it existed) prohibitive for the LHX. Allowing the weapon system to automatically engage threats (off-axis or otherwise) requires a level of sensitivity in detection and recognition capabilities that must be demonstrated to achieve single-pilot operation if the required flight control system cannot be implemented.

b. (U) A further point is the capability of the single pilot to provide suppressive gun fire while simultaneously guiding a missile to the target. During numerous tank engagements while the single pilot was busy guiding the missile to its target, he was effectively engaged and destroyed by other threats. One solution to this problem could be a second aircraft dedicated to protecting the LHX actively engaging the primary target. Fire-and-forget missiles would also reduce the problem to a manageable level.

c. (U) In addition, a fire-and-forget weapon system would make the single-pilot aircraft mission-effective and would alleviate the requirement to bring the aircraft to a hover prior to and during target engagement. Without fire-and-forget weapons, the single-crewman LHX will be less mission-effective and may not survive. Adopting a fire-and-forget weapon system now would significantly reduce the risk for an effective single-pilot aircraft.

5. (U) Maneuvering against and engaging threats. The issue is avoiding and countering the threat with state-of-the-art threat detection and recognition systems. The system must be sufficiently automated to recognize and neutralize a threat while simultaneously providing cues for maneuvering the aircraft to gain a tactical advantage or to avoid the threat kill envelope.

6. (U) Situation awareness. The LHX pilot will live to continue the fight only if he can maintain a high level of situation awareness of the battlefield and the battle evolving around him. The key to the pilot's situation awareness is the displays and the information media available to him. These must be integrated with his strengths and weaknesses in mind. Without a second pilot to aid him when he begins to run out of airspeed, altitude, and ideas at the same time, he must depend on the aircraft systems to maintain a survivable situation until he can regain his composure and once again function effectively. If such a system cannot be provided, then a second crewman must be provided because the nonfunctioning pilot, flying alone on the future battlefield, will die and the Army will have lost one and possibly two expensive assets.

7. (U) Stress. The level of stress while flying an aircraft at high speed and at a very low altitude must be a high priority consideration when dealing with the single-pilot LHX question. Although artificial stress was not introduced into the simulation, pilots flying the simulator consistently identified a high level of fatigue and stress associated with air-to-ground and air-to-air engagements. The point to be made is that, during the benign environment of the engineering simulation, the single pilot was under considerable stress. The stress in combat situations can be expected to be much greater.

(c) (U) Conclusion. The insights gained from the simulation lend themselves to a definition of problem areas which can be expected in the development of the single-pilot LHX. Whether these problems can be overcome by technology and training may be answered by full mission simulations conducted by the ARTI contractors and the National Aeronautics and Space Agency (NASA). These simulations, if planned and conducted in a manner that will evaluate the overall effectiveness of the single-pilot aircraft based on (1) a realistic MEP, (2) a realistic operational environment, and (3) testing the pilot and system to failure, will answer many of the questions raised by engineering simulation to date.

e. (U) LHX Crew Size Trade Study.

(1) (U) History.

(a) (U) The number of crewmembers necessary to perform the tactical aircraft role in military conflicts has been an issue for debate since the birth of military aviation. At the beginning of World War I, combat aircraft were used primarily as scout or reconnaissance aircraft. Most of these aircraft carried a two-man crew (a pilot to fly the aircraft and an observer to perform reconnaissance duties). With the advent of the forward-firing machine gun, aircraft were very vulnerable to attack from their 6 o'clock position. The first solution to this handicap was to equip the observer with a machine gun that could be aimed backward, upward, and sideways. This concept was effective but had its limitations. The weight of the observer, his machine gun, and his cockpit accommodation lowered the fighter's speed, climb rate, maneuverability, and service ceiling. These performance limitations forced the fighter down into the lethal envelope of AAA fire and gave single-seat fighters a considerable advantage in dog fights. Therefore, at the close of World War I, the single-seat concept prevailed.

(b) (U) Prior to and during World War II, almost all of the fighter aircraft produced were single seat. This was primarily due to limited missions and the fact that pilot workload had not increased enough to warrant the need of a second crewmember. Performance factors also contributed to the single-seat configuration. Since airborne radar for fighters did not exist, the air-to-surface missions flown were limited to day visual flight rule (VFR) weather conditions. These types of missions required only one crewmember.

(c) (U) Following World War II, a rethinking of crew complement was required due to the advent of jet propulsion and airborne radar systems. The jet engine increased the speed of fighters and, therefore, required quicker reactions and quicker thinking by the crewmember, thus increasing his workload. The radar allowed for all-weather interception of enemy aircraft and all-weather navigation and weapon delivery. The workload imposed by these two factors forced some of the early jet interceptors into two-seat configurations (F-89, F-94, and F-4). Early jet attack aircraft (F-84, F-86, F-100, F-101A, and F-105) were designed single seat since their primary mission was limited to day visual bombing due to technology limitations preventing all-weather operations. As avionics matured, the capability for performing accurate and safe adverse weather bombing missions became a reality with the A-6 and F-111 aircraft. These were designed with a two-man crew because the workload required to effectively operate the avionics exceeded one man's capabilities.

(d) (U) Today's fighters and ground attack aircraft (F-15, F-16, and F-18) have returned to a single-seat concept. This may be attributed directly to the major advances in computer technology. Automation in new avionics systems assists the pilot tremendously in the areas of navigation, radar interception, target acquisition, and weapons delivery. These aids enable a single crewmember to satisfactorily perform the missions these aircraft were designed to accomplish. These are, primarily, the air-to-air role with air-to-surface capability for day VFR conditions and limited night operations.

(e) (U) In their present form, however, none of these aircraft can perform the night, low-level, adverse weather attack missions as defined by the Air Force or Navy today. They are limited by their lack of a terrain-following navigation system and target acquisition and recognition sensors. Derivatives of the F-15, the F-16, and the F-18 are presently being developed to accomplish these missions. It has been decided that these aircraft will host a two-man crew to enhance mission effectiveness and survivability. Factors affecting this decision include technology, workload requirements, training requirements, and mission, threat, and survivability considerations.

(2) (U) LHX mission environment.

(a) (U) The design of an aircraft (including the number of crewmembers) is greatly influenced by the proposed missions to be flown, the environment (weather, terrain, etc.) in which it will be operating, and the threats which are expected to be encountered during the mission. For the LHX crew size study, the missions considered were: antiarmor, reconnaissance, antipersonnel, and security. Air-to-air combat was included in all missions. A comprehensive description of each of these missions is documented in appendix L. A composite mission scenario was selected as the representative mission for this report and the simulation programs to be conducted for the LHX and ARTI programs. This composite mission was used because it incorporated elements of most all of the missions, provides a good baseline for crewmember task/workload analysis, and simplifies the simulation problem of multiple missions.

(b) (U) The geographical setting is that of the Fulda region of Germany. The environment of this area is one of the most demanding for helicopter low-level/NOE operations worldwide. Low ceilings and limited visibility conditions are common most of the year, thus restricting normal operations. The terrain varies from flatlands to rolling hills to mountains, which tends to make low-level/NOE flight more difficult and hazardous. The cultural features of this area complicate navigation because many of the villages and towns appear virtually alike.

(c) (U) The expected threats and threat density are primary drivers in aircraft and cockpit design considerations. The type of threats to be encountered will be radar/electro-optics (EO) directed AAA, radar/EO/IR SAMs, look-down/shoot-down airborne interceptors, and high-performance threat helicopters. In addition to this already formidable array of threats, the LHX pilot will have to contend with a multitude of automatic weapons and ground obstacles (both natural and man-made). Add to this the nuclear, biological, and chemical (NBC) contamination and obscurants (both natural and man-made), and you have "the dirty battlefield." These threat systems will have very low-altitude coverage capability and will be mobile, thus making mission accomplishment a very difficult task.

(3) (U) Operational concerns. The selection of a crew size for the LHX involves a number of factors, including mission effectiveness, technology availability and risk, program resources, and goals. The crew size decision process must also take into account the operational concerns related to crew size. The operational requirements will demand an aircraft capable of performing a variety of missions as discussed in the mission needs appendix of this TOA report. The discussions of operational concerns in the following paragraphs have been based on the subject matter expert reports found in the annexes, along with inputs received during interviews with operational pilots. The question which the HF/MMI team sought to answer is this: "Is there an operational advantage to the US Army having either a single- or two-seat LHX?" The areas which need to be considered in answering this question include:

-- Operational effectiveness.

-- Flight safety.

-- Training.

-- Survivability.

-- Mission flexibility and growth.

-- Fatigue/stress.

-- Performance.

-- Cost.

-- Risk.

(a) (U) Operational effectiveness.

1. (U) The LHX is to be a multirole aircraft that will perform many diverse missions throughout the world. The multirole mission will make it extremely difficult for the designer to maximize the aircraft capability for each of the specific missions. The final LHX configuration will most likely be a compromise between individual mission requirements, resulting in an aircraft optimized across all missions.

2. (U) The integrated battlefield will require he LHX crew to simultaneously perform a number of mission tasks. For example, during the target acquisition and engagement task, the aircrew will be required to concentrate on the target while watching out for threat ground and air weapons that are trying to kill them and communicating with numerous other members of the combined arms team.

3. (U) There will be situations where the nature of the battle and the mission will overload the single pilot. In general, these situations will occur as a consequence of the LHX pilot being unable to control the pace in which certain functions must be accomplished. During many missions, the communication task alone threatens to overload the pilot. In addition, the effectiveness of the single-pilot LHX can be expected to be less than desired when the pilot is sleepy, tired, or sick or when his thoughts are distracted by personal problems.

4. (U) The target engagement task itself requires a great deal of concentration on the part of the pilot to destroy the target. Any distraction due to other tasks such as responding to threat warnings, communicating with others, or aircraft control will reduce that concentration and degrade performance. Studies regarding aircraft attack missions have indicated that a two-man crew is less easily saturated as the workload increases due to enemy threats or malfunctioning equipment. A two-crew aircraft would allow one crewmember to concentrate on the offensive task of killing targets, while the second crewmember concentrated on the other aspects of the mission such as the defensive tasks. If the LHX were designed to provide one-man operability, as well as the capability for each crewmember to perform specific tasks without a full dependency on the other crewmember, the flexibility of the LHX and its operational effectiveness could be maximized.

5. (U) Observations of personnel involved in the engineering simulation previously mentioned are that the LHX will become highly vulnerable when the pilot workload factor becomes too much for one man to cope with; e.g., engaging targets while flying low level or NOE. Further substantiation of this can be found in numerous NASA workload studies which, in summary, say: Increased automation may have decreased the number of overt responses the aircraft crew may be required to make, but increased system capabilities may have disproportionally reduced the time available to make those remaining responses and/or added new monitoring tasks. The introduction of automation does not necessarily reduce the involvement of the crew in aircraft operations, but only changes it.

6. (U) Operational effectiveness is especially important in this decade since the Army will be fighting outnumbered. Attrition rates in contemporary high-intensity conflicts such as the Yom Kippur War have been significantly higher than for World War II rates, and a war in Central Europe could produce astronomical losses. In view of the projected total number of LHX-SCATs to be fielded, the Army must be sure that it can achieve the maximum possible benefits from its aircraft in terms of enemy weapon systems destroyed.

(b) (U) Flight safety. Since the US Army has no scout or attack aircraft operated by a single crewmember, flight safety data was obtained from the other services. Although other factors such as mission and operational environment prevent a simple comparison between two specific aircraft, the overall safety statistics indicate that, in general, a two-seat aircraft is safer to operate than a single seater. Naval Safety Center statistics show that a two-seat F-4 has a lifetime mishap rate of 2.77 versus 4.79 for the single-pilot F-8. The lifetime mishap rate for the two-seat A-6 is 1.52 as compared to 2.66 for the single-place A-7 aircraft. The A-6 had five pilot error mishaps versus 41 pilot error mishaps for the A-7. The data reviewed for the Air Force and the Navy aircraft mishaps, although not directly equated to the helicopter environment, does indicate a two-crewmember aircraft may provide an extra margin of safety. The majority of aircraft mishaps have pilot error as a contributing factor, many involving mistakes where the pilot fails to notice an emergency situation or fails to follow the procedural methods in a timely manner. This could easily occur during the heat of battle in a single-crew LHX when the pilot is concentrating on mission success. The presence of a second crewmember would permit a more effective handling of such situations. In the NOE environment, the second crewmember would free the pilot from a number of crewstation duties and allow him to concentrate on flying the aircraft. From a flight safety aspect, a two-seat LHX could prove to be more cost-effective than a single seater.

(c) (U) Training. A detailed assessment of the LHX training considerations is covered in appendix U. This section discusses those training concerns that are more directly related to the crew size issue.

1. (U) Seasoning process.

a. (U) The training and seasoning process currently in place allows for the aviator to be approximately 75 percent operationally ready when he leaves the training base. He must then be paired with an experienced aviator at the unit to learn from the experienced pilot. During the Vietnam War, this "seasoning process" used by both the Army and the Air Force proved very effective. A single-place aircraft would require additional training at the institutional base and would prohibit the use of the training and "seasoning process" as currently practiced. Since effectiveness and the survival of the new guy are directly related to the learning curve, the "seasoning process" is an important consideration for the LHX.

b. (U) Historical studies indicate that, in a single-place aircraft operated by a pilot without combat experience, the pilot's chances of surviving the first engagement are less than 50-50. The probability of survival increases with experience level. For a two-seat aircraft, with an experienced/new pilot mixture, the new pilot would enjoy approximately the same probability of survival as the more experienced pilot/aircraft commander (figure R-16). The probability of survival is based on the exposure and experience of the aviator.

c. (U) With current training strategy, it is assumed that, at the time of graduation from flight school, the novice aviator does not necessarily require full proficiency in his mission aircraft or its subsystems. It is expected that a considerable amount of learning and skill improvement will take place under the guidance of more experienced aviators. Even after a new pilot has obtained status as pilot in command, it is common practice to pair him with more experienced aviators when flying until he has sufficient experience and self-confidence to fly with less experienced copilots. The single-seat aircraft would not permit such a training strategy to continue.

2. (U) Training requirements.

a. (U) A basic requirement for preparing aviators to employ a single-seat SCAT aircraft will be a two-seat trainer. In reviewing the flight and mission tasks for which LHX-SCAT aviators must be trained, approximately 170 were identified which should require a reasonable level of proficiency before being executed or practiced solo. Many of these tasks, notably emergency, instrument flight, and weapon employment procedures, can be trained adequately using simulators. However, there are a considerable number of activities, central to scout and attack mission tactics, which cannot be adequately trained in simulators using current technology. Proficient performance of these activities requires precision timing and control responses based on fine discrimination of sensory cues (visual, auditory, and vestibular) which involve too much detail and subtlety to be accurately simulated at reasonable costs. They include:

(1) (U) Terrain flight and maneuvering.

(2) (U) Simultaneous terrain flight and target engagement techniques.

(3) (U) Confined area operations.

(4) (U) Touchdown maneuvers such as autorotation and slope landings.

b. (U) Since the tasks comprising each of these groupings all involve significant safety risks, they should be practiced under direct supervision of a qualified instructor pilot until students develop sufficient skill to safely continue practicing them solo.

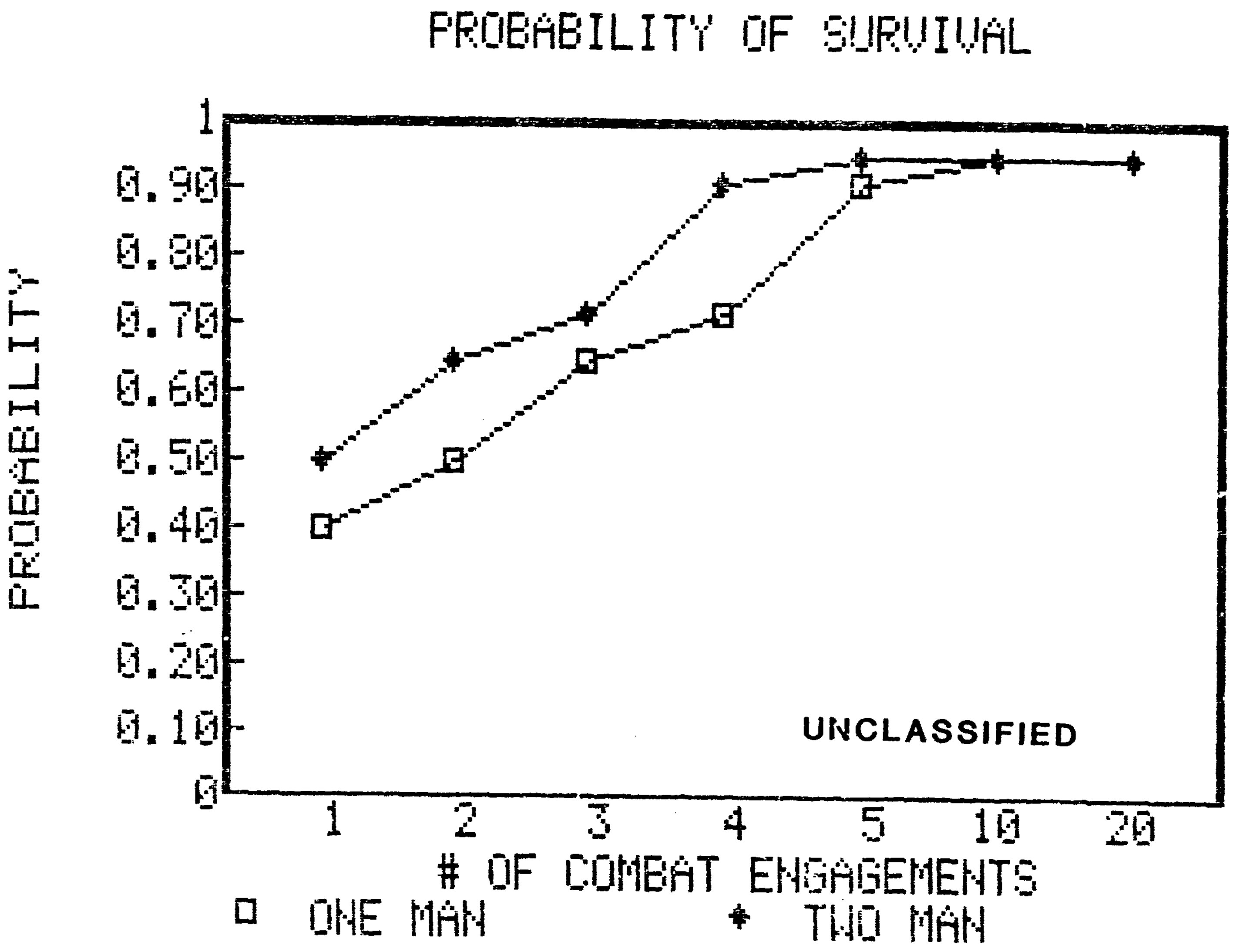


Figure R-16. (U) Probability of survival.

3. (U) Aviator requirements.

a. (U) While interviewing Navy, Air Force, and Marine Corps operational pilots, many of them conveyed their concerns for the average pilot trying to operate complex systems such as those found on the F/A-18. Both F-18 and F-15 pilots mentioned that it was almost impossible to learn, much less maintain proficiency in, all of the many capabilities of each and every system on the aircraft. The F-15 target acquisition and fire control radar is a good example; pilot interviews indicate that it is a major effort to learn its many modes of use. To handle the problem while in flight, they usually develop combat skills in only three or four operational modes. This indicates that the aircraft has more system capabilities than the pilot is able to utilize. (The above comments were made by aviators with college degrees, often with engineering backgrounds, and more extensive flight training than that received by Army aviators.)

b. (U) The pilot of a single-seat LHX may have to have superior mental capabilities. This type of soldier will be in short supply and high demand by other branches and specialties. Because of this, the single-seat LHX may not have the desired impact on the Army's manpower requirements. The availability of pilots with the ability to handle such complex systems while flying the aircraft without the benefit of additional unit seasoning may be an even more serious problem than just a numbers problem. It may be that the single-place aircraft will not require additional pilots to meet the 24-hour operational capability, but if it requires such high-caliber people to use it, have we not, in fact, compounded the pilot availability problem? Pilot availability problems will not disappear with the single-place aircraft. This is evidenced by the Navy which continues to have pilot availability problems even though they have fielded a number of single-place aircraft. Entrance and training requirements for Naval aviators can be viewed as major causes of the continuing problem. A two-man crew (not necessarily both rated) would reduce the requirements for the type of man selected and the degree of training required for any one individual.

(d) (U) Survivability.

1. (U) A conventional war between the North Atlantic Treaty Organization (NATO) and the Warsaw Pact would engage masses of aircraft, tanks, troops, and specialized weapons. At its heart would be electronic warfare (EW) and ECM, especially in air defense operations. Pilots would be expected to penetrate the most sophisticated SAM and AAA belts ever fielded.

2. (U) A typical Warsaw Pact army of four or five divisions has an air defense system near the forward edge of the battle area covering a Front about 50 km long and 100 km deep. Such an Army typically has 32 batteries of ZSU-23-4s, 23 batteries of S-50 AAA, 5 batteries of SA-6 SAM, 9 batteries of SA-4 SAM, and 3 batteries of SA-2 SAM, plus ubiquitous shoulder-fired SA-7s, quadruple SA-9s, command-guided SA-8s mounted on vehicles, and individual automatic weapons. Large numbers of overlapping early warning, ground control, intercept, and acquisition radars tie these factors together.

3. (U) Just the magnitude of individual weapons presents problems. Since the threat is made up of so many different systems pointing from many different areas, aircrews will be faced with warning from all quarters. Not only will the radar warning receiver light up in all directions, but the headset tones may be continuous. This can be confusing and distracting, forcing a "head in the cockpit" reaction. Many Vietnam and Middle East combat veterans consider this very dangerous since a crewmember's eyes are often his most effective piece of ASE. In past conflicts, an often used enemy trick was to set up multiple automatic firing positions. One would fire at the aircraft to distract the pilot while another, unless observed by a second crewmember, would make the kill. Based on the LHX missions and threat assessment, this type of situation can be expected to be repeated in future engagements with one exception: the second crewmember will not be present. Another point to consider is that, during combat, the aircrew which detects the enemy first has a decided advantage in making the kill and increasing their own probability of survival. The second crewmember can make that happen.

4. (U) When pilots and designers talk about survivability, SAMs seem to be the preferred subject; however, there is every reason to believe that, with the exception of the shoulder-fired SAMs, the ZSU-23-4 and smaller antiaircraft guns will continue to be the greatest threat to Army aviation. Modeling conducted during the LHX TOA showed that, by virtue of having crew redundancy, the two-place LHX was approximately 25 percent more survivable against all threats modeled. For a more detailed analysis of the survivability aspects of the one- versus two-crewmember issue, refer to the survivability appendix of the TOA (appendix Q).

(e) (U) Mission growth and flexibility. Historically, the design of single-seat aircraft is oriented toward a specific mission or series of missions predicated on the assumed threat at the time of system development. As rapidly as these systems are placed in combat, the increased threat and operational conditions require them to be modified. New capabilities are added that tend to place an increased workload burden on the pilot. The next step is often to design a new version of the aircraft with two seats. This cycle has been repeated throughout aviation history. The LHX will probably be no exception.

1. (U) The LHX is projected to have a 25-percent growth factor built in. Advances in mission avionics and weapons make this a conservative estimate. The accomplishment of the new missions will be made possible with additional components added to the aircraft as needed.

2. (U) If the answer to more capability is the addition of new systems to the crew station, that potential growth may be limited by the single pilot operating at maximum capacity. This will be especially true when an aircraft system malfunctions and the pilot has to "take up the slack." Designing the LHX for two seats initially could enhance the system's operational flexibility and be of great benefit in adapting to the mission changes expected over the service life of the LHX.

(f) (U) Fatigue/stress.

1. (U) Current Army flight regulations (Army Regulation 95-1) specify the number of flight hours which can be logged per day as a function of type of flight profile, environmental conditions, and number of engagement days. Studies dealing with combat fatigue have reported that 10 combat days are equivalent to 17 calendar days of normal flying. As a rule, pilots are expected to be able to fly between 8 and 12 hours a day. During surge operations (or the independent actions of an Army 21 close combat force), pilots may be called upon to fly considerably more hours than normal, as well as attending to additional duties. The net result will be fatigue. The LHX envisioned is expected to be superior in the management of workload and release from tedious tasks; however, the price paid will be increased cognitive involvement by the pilot. While the effects of fatigue upon aviators is a topic still being researched, it is safe to assume that lack of sleep, coupled with long flight hours, will take its toll upon the pilot's ability to comprehend and react to the aircraft and the tactical situation.

2. (U) Only high-fidelity simulation training and stressful flight time in the aircraft will protect the pilot from the immediate effect of high-intensity stress. A realistic rest and relaxation policy, coupled with psychological decompression techniques, will also be required to extend the pilot's effectiveness. However, even when a soldier is provided with realistic and imaginative familiarization training and has formed a generally accurate picture of combat conditions, there will nonetheless remain a gap between his mental preparation and his first experience of being fired upon. Nothing can prepare you for the experience of being fired upon. The realization that these people mean to kill you has a severe impact on your psychological well-being and performance.

3. (U) The overall effect of the fatigue and psychological impact will be that the pilot's normal skill may break down and he may begin to deal with separate component requirements and not be able to integrate them into the integrated requirements and responses. Not only will there be a demonstrable fall in the level of performance, but flight safety will also be jeopardized in that the pilot will accept a lower standard of performance. He may take unnecessary risks with a consequent reduction of safety margins; hence, there will be an increase in the probability of an incident or accident. A significant finding of aviation fatigue research was the increase in the number of errors toward the end of a flight as if the pilot felt that, having accomplished the bulk of his mission, he could relax. Given the reduced number of crewmembers and the requirement for longer missions, we can expect a significant increase in fatigue-related mishaps

4. (U) The impact of fatigue and stress on the LHX crew size is significant in that, with a single pilot, there will possibly be a decrease in performance simply because he is required to accomplish numerous tasks while simultaneously monitoring other tasks without any significant relief throughout multiple missions. The question which must be answered is whether a single pilot or two pilots will best be able to perform at acceptable levels of effectiveness and survive for an extended period of combat. The dynamics

of the integrated battlefield will surely create situations where a very tired LHX pilot will be required to conduct an in-flight change of mission and end up a considerable distance away from his parent unit where a relatively "rested" aviator is waiting without an aircraft to relieve him.

5. (U) Although the effect of isolation on the LHX single pilot remains an unknown, historical data shows conclusively that soldiers fight more aggressively and effectively as a team. The two-man foxhole concept was derived from combat experience with a one-man foxhole. The two-man foxhole has proven to be more effective. The same concept can carry over to the crew of the LHX. The LHX pilot may very well spend over half of his total mission time in direct confrontation with the enemy. The utilization of forward arming and refueling points will produce more time on station which will result in repetitive engagements with the enemy without any extended rest. The Air Force and Navy have for a long time used the wingman concept which, under most cases, permits a pilot to have eye-to-eye contact with another individual. The LHX, however, cannot use such a concept as effectively because of the need to remain dispersed and hidden from the enemy. The LHX pilot may, in fact, go through a complete mission without seeing any other individuals except those on the ground trying to kill him. Without a doubt, Army pilots are extremely aggressive and capable but have never before had to deal with complete combat isolation over long periods of time. Based on past combat experiences, it may be a problem that will reduce overall mission effectiveness. A two-crew LHX would do much to relieve that problem.

(g) (U) Performance. Consideration of a single-seat aircraft raises the fundamental question: How much larger would the two-place aircraft be and how much performance would be lost? Although the Army has no experience with designing a true single-seat helicopter, projections by both the government and the contractors put the projected difference somewhere between 600 and 750 pounds. This may be an overestimate when the increased mission equipment and ballistic protection is provided for the single pilot. Although exact performance figures are not yet available, performance degradation for the two-place aircraft should not be a major factor if the decision is made early enough to allow innovative design studies. However, if a decision for the one-man LHX is made and it is later proven that it will not work, the LHX program will have to stop while the redesign of a two-place aircraft which meets requirements is completed. This would not be the case for the less risky two-place design. The extra space could be filled with additional fuel, mission equipment, or armament, or a second pilot when required.

(h) (U) Cost.

1. (U) A single-seat LHX has one main advantage—lower production and operating costs. For comparable speed and endurance, it is projected that it will be about 15 percent lighter in empty weight and in gross weight than its two-seat counterpart. These lighter weights should translate into lower airframe and recurring production costs--costs which are generally proportional to airframe weight. Since the engine has been sized at 1,200 shaft horsepower, there would be no significant savings associated with the engine. Some of the recurring cost advantages of a single-seat LHX would be offset by

the higher development and testing cost of the automation features required for a single pilot. There may also be significant added recurring costs for the extra sensors and computational capability associated with the single-crew LHX. The net effect is that the production unit cost of the single-seat aircraft is expected to be somewhat less than its two-seat counterpart.

2. (U) A possible disadvantage often associated with the two-seat aircraft is the inceased life cycle cost of the aircraft. However, if just one of the second crewmembers in a "flight" of five two-seat LHX's sights an enemy threat or identifies an unsafe flight condition and saves his aircraft, he would in effect "pay" for the life cycle cost of having the second man in the aircraft for the entire flight. Thus, it seems that the backseater would be cost-effective in increased survivability and safety alone.

(i) (U) Risk. Prior to the TOD and the TOA, contractors were asked to explore the possibility of building a single-pilot SCAT aircraft. The contractors provided the government with data which alluded to a highly advanced, highly automated aircraft which constituted a high-risk program. Based on the HF/MMI analysis, the single-pilot crew station constitutes a higher risk than the two-place crew station. The single-pilot aircraft will require more extensive automation and crewstation integration than a two-place aircraft.

(j) (U) Summary. From an operational and mission performance standpoint, the two-crew LHX appears to be the better choice. The analysis of the operational concerns indicates that a two-crew LHX will be more survivable, more operationally effective, and safer to fly. The second person in the crewstation can reduce the effects of fatigue and stress and provide considerable flexibility in mission performance and growth. It is also estimated that training effectiveness will be enhanced and cost will be less with a two-seat LHX. The main disadvantage of the two-seat configuration is the predicted production and life cycle cost which is expected to be only slightly higher than a single-seat version.

f. (U) Integrated Crewstation.

(1) (U) Overview.

(a) (U) The combat effectiveness of the LHX largely depends on the aircrew's ability to successfully operate the aircraft and its onboard equipment and systems in flight. To obtain the best overall operational effectiveness, the interface between the aircrew and the aircraft must be designed to effectively capitalize on the capabilities of technology and the aircrew.

(b) (U) Early crewstation designs were relatively uncluttered and contained only minimal instrumentation, displays, controls, and flight systems necessary for optimal daylight flying. These systems were well within the capabilities and workload limitations of the aircrews. As the full potential of Army aircraft was realized, mission requirements and aircraft crewstation configurations began to change. New dedicated devices and systems were added, each competing for the limited space within the FOV and reach of the aviator.

Each new function or system added usually resulted in the addition of one or more dedicated displays or controls. Due to the limited space within the crewstation, it was not always possible to place the new controls or displays in a position that maximized human effectiveness.

(c) (U) The additional workload imposed by the large variety of systems incorporated into the crewstations was further complicated by more demanding missions. When the primary Army aviation mission was combat support, transporting soldiers and equipment at relatively high altitudes, aviators were afforded more than sufficient time to cross-check instruments, tune radios, monitor their crewstation systems, and fly the aircraft. With the addition of close combat missions and the advent of highly sophisticated ground-to-air weapons deployed by the enemy, Army aviation was required to change tactics. The luxury of flying well above the terrain is no longer affordable. Helicopters are now required to utilize terrain flight techniques, often flying below treetop levels to avoid enemy detection. When flying in the terrain flight regime, most of the aviator's attention must be concentrated outside the aircraft, leaving little time for monitoring instruments or operating controls and systems inside the crewstation.

(d) (U) The requirement to be able to fly and fight around the clock further compounds the problem. When flying at night or at reduced visibility levels, the aviator's capability to see things outside the aircraft is greatly reduced. To ease the burden of flight at night, new technologies like image intensification night vision goggles (NVG), low-light level video cameras (LLTV), and IR video systems have been incorporated into Army helicopters. These systems do provide an enhanced night flight capability, but they have increased the number of displays and controls the aviators of dual-crew aircraft must be attentive to, thereby increasing the aircrew workload.

(e) (U) The increased demands of future conflicts, coupled with the addition of new and more complex systems in the crewstation, could easily reach a point where, if not properly integrated, the crew workload or attention level may prevent obtaining the maximum effectiveness from the aircrew and the aircraft in the highly intense and dynamic conflicts of the future.

(f) (U) Technological advances over the past years have demonstrated a considerable increase in the capability of aviation systems and mission equipment. Human or aircrew capabilities, on the other hand, have increased in the domain of knowledge and training, but the aircrew's cognitive and sensory capabilities, anthropometry, and environmental requirements have changed very little. For example, the capability to present visual information on displays in the cockpit has changed from the dedicated dial and moving needle to graphically presenting information on electronic displays. The aviator's visual capabilities and limitations, on the other hand, remain essentially the same as they were in the past. To assure the success of the LHX in future conflicts, aircrew workload must not be allowed to exceed a level that restricts the effective use of the full aircraft capabilities.

(g) (U) Applying advanced technology is certainly an appropriate way to improve performance and overcome the space and weight limitations in modern aircraft, as long as its use remains within the abilities and capabilities of the aircrew that must operate the system. The change from current crewstation configurations to a more sophisticated design is expected to shift the crew workload from one that is manual or physical to one that is more demanding from a cognitive and mental workload aspect. In effect, the aviator whose past role was one of system operator and information integrator becomes a system manager.

(h) (U) Electronics and avionics systems may be available in the LHX development time period that can gather and provide all the information needed to fight and win future conflicts. The information can, however, only be useful if presented to the aircrew at a rate they can assimilate and effectively use. To best optimize available technology, it is vital that the aircrew be provided essential flight and mission information in a way that allows them to become an integral part of the system. The operation of advanced Army combat aircraft demands that information be organized and presented so that the aircrew will be provided with preprocessed data relevant to the specific mission or flight phase they are engaged in.

(i) (U) The challenge in the LHX is to maximize system performance through the appropriate assignment of mission functions to the aircrew and the aircraft in a way that uses the best attributes of both man and machine. The crewstation displays and controls, with which the aircrew interact, must be designed to capitalize on the crew's capabilities. One of the goals of the LHX program is to design an aircraft that is mission effective with a single crewmember. To accomplish that goal, the functions now performed by the second crewmember in current aircraft must be automated or transfered to the single crewmember.

(j) (U) Flying at low levels and NOE below treetop levels is extremely demanding on the flight crew. NOE flight requires the pilot to focus most of his visual attention outside the crewstation while rapidly maneuvering the aircraft around obstacles in the flight path. Add the other crew tasks like navigation, communication, target acquisition and engagement, and monitoring of the aircraft subsystems, and the demand on the aircrew's physical and mental abilities rapidly increases. The requirement to fly and fight around the clock further compounds the problem.

(k) (U) The increasingly hostile environment Army aviators must fight in and the number and complexity of new aviation systems requires that a large amount of information be presented to and assimilated by the aircrew. The most essential ingredient of the design of the LHX for the future battlefield is the integration of the vast amount of information provided by the aircraft sensors into a form that can easily be interpreted and used by the aircrew.

(l) (U) The goal of a single-crewmember LHX demands an even more efficient crewstation design. The full integration of the information displays, the control techniques employed, and the capabilities and limitations of the aircrew at a level much greater than current aircraft is mandatory if that goal is to be achieved.

(m) (U) The functions the aircrew must perform in the LHX fall into the major functional areas of flight control, navigation, communication, target acquisition and engagement, survivability, and system status monitoring. Each of these functions is of prime importance when the LHX enters combat. The inability of the aircrew to effectively perform any one of these functions could result in degraded performance and loss of mission success.

(n) (U) A review of the crewstation integration of recently developed aircraft supports that hypothesis. Both the AH-64 attack helicopter and the OH-58D scout helicopter require a crew of two to perform their missions even though some of the technology and crewstation integration proposed for the LHX can be found in those helicopters.

(o) (U) In a single-crew LHX, many of the crew duties must be automated to take up the slack left by the second crewmember. That automation must be extensive and flexible enough to provide the crew the option to use whatever automation is best suited for the particular mission they are involved in at a specific time.

(p) (U) A review of the major human factors engineering issues of the LHX crewstation integration concerns has indicated that the capabilities and limitations of the human must receive additional consideration. The LHX is expected to be a highly automated helicopter with the capability to provide the aircrew with a continuous flow of essential information. It is the integration of that information into the crewstation, along with the processing of that information by the crewmembers and the resulting control actions on the part of the aircraft, that require much attention from the human factors engineering viewpoint. Traditionally, the system design phase, making the hardware work, has consumed most of the allotted time scheduled for development of a new aircraft. If the LHX is to truly provide the effective combat system needed to meet the future threat, the human factors engineering effort must be given as equal an emphasis as the hardware operational design. The human factors engineering analyses presented in the Aviation Systems Command TOD and this Trainign and Doctrine Command TOA, along with the preliminary results provided thus far from the ARTI program, all contribute to the assessment of the soldier-machine interface of the LHX and the enhancement of the crew's operational capabilities and the manpower, personnel, and training requirements. These preliminary efforts provide a framework for the development of the LHX but do not answer all the human factors engineering-related issues. Human factors engineering for the LHX crewstation is part of an iterative design process that must be continually reviewed and updated. The operational success of the LHX on the battlefield is dependent on that process continuing.

(q) (U) The next several pages in this appendix will address various aspects of the LHX crewstation and will examine some of the crew functions upon which the new technology may have a positive impact. Workload is considered in light of the time spent on specific crew activities or the attention aviators must devote to any specific aircraft function. The major areas considered include: navigation, communications, flight controls, subsystem monitoring, target acquisition/designation, survivability systems, NBC protection, life support equipment, and controls and displays. Each of those areas is discussed separately but, in the final LHX configuration, it is essential that they be fully integrated to provide minimal workload for the aircrew. The major sources of information considered in this analysis included the Army Aviation Mission Area Analysis, the LHX TOD, and the individual reports submitted for inclusion in the US Army Aviation Center's TOA. It is assumed that the detailed design of the airframe, the crewstation, and the controls and displays will incorporate all human engineering principles and data regarding the physiological and mental capabilities and limitations of the air and ground crews expected to operate, maintain, rearm, and refuel the LHX.

(2) (U) Navigation.

(a) (U) The success of the LHX in future conflicts will be highly dependent upon the ability of the aircrew to maneuver their aircraft to the right place at the right time. That ability, in turn, depends on being able to successfully perform the task of navigation. In that regard, navigation encompasses not only movement from one point on the battlefield to another but the ability to accurately accumulate, record, use, and transmit position information concerning the threat and friendly forces. Mission success also requires the crew to maintain an overall situation awareness of the rapidly changing tactical situation around them.

(b) (U) Studies and evaluations of the relationship between human performance and currently fielded navigation systems reveal that they yield performance less than that needed for the LHX. This less-than-desired performance is due, in part, to a number of factors including loss of perspective, map design, navigation sensor accuracy, and display designs. Evaluations of more recently developed and available navigation systems indicate these systems do much to enhance the present capabilities to navigate and to maintain a situational awareness of the battlefield, but further improvements are needed if the maximum effectiveness of the LHX capabilities is to be realized.

(c) (U) Projected map displays (PMD), utilizing remote map reader technology that takes map information stored on film and projects it onto a multifunction display, improve current systems by taking the traditional map information out of the aviator's lap and placing it on a display in the instrument panel of the aircraft. In tests conducted so far, an aircrew of two, when using a projected map, can navigate terrain more rapidly with fewer delays and course disorientation and less visual attention devoted to the navigation task than previous navigation systems. The copilot/navigator does, however, still devote about one-fourth of his total visual attention to the navigation system. In addition, the navigation system requires manual updating after every 10 to 15 minutes of flight.

(d) (U) Digital map technology, because of its inherent flexibility, provides the greatest potential for mission success in the LHX. The digital map approach uses as its source of information geographic data produced by the

Defense Mapping Agency in a digital form that can be stored in the memory of flight computers. During flight, this data is converted back into a display that can be used by the aircrew. The digital map technology not only has the potential to provide a horizontal display much like the PMD but, when fully developed, it could provide a vertical display as well. Another advantage of the digital map system is the capability for the aircrew to select the type and amount of information to be displayed. Because of their common tri-service use by both ground and air forces, current paper maps and projected map displays often contain more information than can be used by Army aviators. With the digitally generated data base, only the information that the aviator chooses is presented on the crewstation display. In a sense, the digital map display can be decluttered. The digital map system also has the potential to automatically calculate and display the optimal flight path the aircraft can follow to best avoid the known threats. The exact level of visual attention and crew workload required by the digital map system has not yet been determined. The available systems are still in the simulation evaluation stage. It is speculated that the visual attention will be less than that of the PMD, but it could still be relatively high. If the visual attention and crew workload associated with the panel-mounted digital navigation system approaches that of the panel-mounted display, additional display techniques will be necessary to enhance the LHX performance, specifically in a single-crew LHX. While flying missions at terrain flight levels, the single crewmember should devote as much visual time outside the crewstation as possible. He can ill afford to spend one-fourth of his attention on the navigation task. Navigation information should, therefore, be provided to the aviator in a manner that allows him to keep his eyes outside the crewstation during terrain flight. Simulation and flight tests to specifically address the most effective means of providing navigation information to the aircrew, when their attention is focused outside, will be necessary if maximum effectiveness of the LHX is to be obtained.

(e) (U) The digital map data base also has the potential to provide inputs into an automatic terrain following and avoidance system. With such a system, the pilot could be relieved of much of the workload associated with the task of flying. That technology, unfortunately, has not yet matured. The current digital data base with approximately 100-meter (m) accuracy, along with sensors to detect small objects like buildings, trees, and wires, require considerable improvement if full terrain following and avoidance are to be achieved.

(f) (U) The LHX navigation system review indicates that, at a minimum, a horizontal situation map-like display should be provided that gives the aircrew real-time accurate, spatial information concerning their aircraft position and the position of friendly and threat forces during day, night, and adverse weather conditions. In addition, the system should allow the aircrew to rapidly obtain information from the display with minimal head-down time inside the crewstation, provide a means to automatically update the position information, allow the user to annotate the display with friendly and threat information, and provide the capability to rapidly transfer information to other members of the combined arms team. The need to develop methods and techniques to allow the aviator to keep his attention focused outside the aircraft while navigating is of particular importance to the single-crew aircraft where the copilot is no longer available to attend to the navigator's task. From a human factors engineering perspective, the potential of the digital-based navigation system appears to provide the better choice to the LHX, assuming the systems currently under development are sufficiently mature by the full-scale development phase of the LHX. If the goal for a single-crew LHX is to be accomplished, a high priority must be placed on the improvement of navigation sensor accuracy, the availability and accuracy of digital data base information, and improved methods for displaying navigation information to the aircrew.

(g) (U) Any candidate navigation system for the LHX should be considered in terms of the system workload demand. Navigation systems typically demand to be fed information during system start-up and alignment, flight planning, sensor updating, and en route waypoint entry. Currently fielded systems require from 5 to 20 minutes to load data through a keyboard during the pre-takeoff phase of the mission. Updating the navigation system accuracy is required on a frequent basis during the mission, and the crew must spend valuable time telling the navigation system its present position so that it can then tell the crew their present position for the next few minutes. Data loading should be achievable in the aircraft without using a keyboard and should not require more than a few minutes. System updating should be infrequently required and should be easily accomplished. The navigation system should support the pilot in the performance of his mission and should minimize the demand on his time and attention.

(3) (U) Nuclear, biological, and chemical (NBC) defense.

(a) (U) Army aviation can expect to encounter NBC threat weapons during future conflicts. The Soviet Union and Soviet-backed forces have the capability of employing a vast array of such weapons and the capability to protect their own troops during such an attack. The LHX must incorporate design features that can successfully counter that threat. Analyses of NBC defensive measures have highlighted three basic approaches that can be used to protect the aircrew from the threat: contamination avoidance, collective protection, and individual protection.

(b) (U) The most effective means to prevent casualties and protect the aircraft from the NBC threat is perhaps avoiding the threat completely. Although contamination avoidance may not be used in all cases, it is an available tactical measure for the commander in the field when the situation permits. The option of contamination avoidance will be successful only if aviation units are provided a reliable means to determine if an attack is imminent or has occurred. The ideal situation would be the identification of contaminated areas at some standoff distance from the aircraft. Remote standoff detection devices are required for the LHX to fully exercise the option of contamination avoidance. Detectors in the inventory are of the point sampling type normally used on the ground. As such, they must be placed in the contaminated area to detect the contamination. Preliminary flight testing has indicated that it is possible to modify some of those systems for flight use. Standoff detectors, on the other hand, are in the early development phase. If a standoff detection capability is to be achievable for the initial fielding of the LHX, those programs need to be given a priority equal to the LHX program. Contamination avoidance is a tactical measure that can be advantageously used when the combat situation permits, but it does not provide a complete solution to the NBC threat.

(c) (U) Collective protection, provided to the aircrew by way of an LHX that is completely sealed and pressurized to prevent contaminated agents from entering the aircraft, would also provide a considerable tactical advantage. Collective protection would allow personnel to operate in normal flight clothing, thereby overcoming the performance decrements imposed by protective clothing. In addition, collective protection would also protect the aircraft avionics, aircraft materials, and other equipment or systems inside the aircraft from destructive agents. The need for decontamination of the interior of the aircraft would also be reduced. Collective protection, however, cannot assure total survival of the LHX on the battlefield. Full protection could be lost in the event of damage by enemy fire that breaks the integrity of the sealed aircraft or when it is necessary for the aircrew or passengers to enter or exit the aircraft in a contaminated area. Collective protection alone is also not the solution.

(d) (U) Current protective clothing that encapsulates the individual in an NBC protective suit and mask provides a life-saving capability, while allowing the individual to continue to operate on the battlefield but at a considerably reduced level of effectiveness. The protective clothing and masks introduce problems associated with degraded crew performance like heat stress in hot climates, restricted aviator movements, a lack of manual dexterity and sensitivity of touch, a restricted FOV, reduced visual capabilities, increased aviator workload, and fatigue. All these factors combine to create a large decrement in crew performance. Individual protection much like collective protection and contamination avoidance allows the aircrew to continue the battle but, alone, is not the optimal way to meet the NBC threat.

(e) (U) The most viable solution for the LHX appears to be a hybrid collective protection system that maximizes the advantages of all three approaches: contamination avoidance, collective protection, and individual protection. Such a system could allow the aircrew to operate in a pressurized aircraft, partially clothed in NBC gear under normal or routine conditions. The contaminated area could be avoided when onboard detectors warn of its existence ahead of time and the battle conditions allow the commander to exercise this option. When approaching a known contaminated area or when the aircraft detectors indicate the aircraft is in a contaminated area, the full NBC protective measures could be taken. This approach would allow for maximum crew effectiveness to be obtained when not in a contaminated area, as well as assure protection to the aircrew when in a contaminated area. The technology to do this appears to be available well within the LHX development time frame.

(f) (U) To take full advantage of this concept, NBC agent detectors should be located both inside and outside the aircraft. The aircrew would then be able to determine when they are in a contaminated area and whether the contamination has penetrated the crewstation. A remote standoff detection capability should be added, when available, to avoid the contamination completely. A sufficient cooling capability must also be incorporated into the crewstation to prevent aviator heat stress in hot environments. The use of aircraft environmental control systems, in conjunction with microclimate cooling vests worn by the aviator, appears to meet this need.

(g) (U) In addition to the hybrid system and cooling provisions, the crewstation configuration and the design of the controls and displays should provide adequate room and space for the aviators to operate the LHX when fully dressed in NBC clothing and other life support equipment.

(4) (U) Flight control.

(a) (U) The helicopter is basically an unstable, vibrating platform suspended in space by a spinning rotor blade. The task of the aviators when flying such a system is twofold. First, the aviators must fly the aircraft from one location to another; second, they must maneuver the helicopter into a position so that they can effectively complete their combat mission and defeat the enemy. To accomplish that task, the helicopter itself must be extremely agile and maneuverable. The flight controls of current Army helicopters consist of three separate control levers that control mechanical systems with hydraulic boost. Two of the control levers require manipulation by the aviator's hands while the third is moved by the aviator's feet. A review of the evaluations concerning manual control and workload suggests that, even under the most favorable conditions, a large percentage of the pilot's attention is required for manual control of the helicopter. That effort is particularly demanding during mission conditions involving poor visibility, variable winds, and terrain flight where the aircrew is continuously maneuvering around trees and obstacles. At a minimum, the LHX should provide some level of automatic control and stability augmentation to assist the aviator and reduce the amount of attention, control movement requirements, and workload imposed on the aircrew. The less attention the pilot must devote to the task of controlling the aircraft, the more time he will have to perform other operational functions, thus enhancing the probability of mission accomplishment. This is specifically important during terrain flight where the fatigue factor is 1.3 times higher than during normal flight.

(b) (U) Another aspect of crew workload associated with flight controls is the physical interface between those controls and the human operator. Aviators in today's Army come in all sizes and shapes. It is difficult to design a crewstation that will properly accommodate all of these. If the crewstation is not optimally designed, the adverse effects on the human will degrade operator performance. Investigations directed toward the evaluation of aircrew anthropometeric dimensions and crewstation configurations have pointed out that in current helicopters the crewstation internal space, in combination with the fixed cyclic control position, does have an adverse effect on the aviator. To reach the cyclic control grip while simultaneously resting their arm on their leg, a number of aviators are required to assume an exaggerated forward "slouched" position. That position places a curvature in the human spine that is susceptible to vibrational stress and fatigue during normal flight, resulting in back problems for the aviator. The "slouched" position also increases the probability of back injury during a crash. In addition, the forward "slouch" position tends to restrict the aviator's forward vision outside the aircraft and to shift his eye position away from the optimal design eye position used for reference when determining the placement of controls and displays in the crewstation.

(c) (U) Aircrew protective gear and life support equipment also create an interface problem with current aircraft controls. Larger aviators, wearing full NBC gear and body armor, often restrict the full movement of aircraft controls. The situation can be partially relieved through a better seat and aircraft control position relationship. Improved adjustments on both the seat and the control levers in both the horizontal and vertical planes would be one way to reduce the need for the aviators to "slouch" when flying.

(d) (U) A second solution would be to remove the position constraints imposed on the aviator with current type aircraft controls (cyclic, collective, pedals) by replacing them with a single "side-arm controller" that could be operated with one hand. One such system, the advanced digital/optical control system (ADOCS), is undergoing development. From a human factors perspective, the "side-arm controller" has a number of advantages. First of all, the aviators should no longer need to "slouch" forward in the crew seat to reach the flight controls. Second, the aircrew should be afforded more freedom to position their bodies in a more comfortable position in the aircraft. Third, the relocation of the cyclic control function from in front of the aviator would remove one of the visual restrictions between the aviator and his instrument panel. The relocation of the collective control head would also remove the visual restriction between the pilot and the avionics control panels in the center console. The increased, unrestricted FOV not only enhances the aircrew's capabilities but allows the crewstation designer more freedom in which to place displays in the crewstation.

(e) (U) From a handling qualities point of view, the use of fly-by-light and likewise fly-by-wire concepts should afford more flexibility to design the aircraft control system in such a manner that aviator workload and attention devoted to the flying task are reduced. With such a system, control gains and transfer functions could be tailored to provide the best controllability for various maneuvers. Such tailoring could be selected by the pilot or perhaps automatically by sensing appropriate aircraft state variables or operator inputs. It would also provide an avenue whereby information from other aircraft system sensors could be inserted into the control loop for increased automation of the flight control function.

(f) (U) Flight control and maneuvering of the aircraft is an attention-consuming task for the pilot during flight when well above the terrain. Terrain flight down among the trees and obstacles is much more demanding. Based on studies of current helicopters, the pilot of a two-crew aircraft must devote most of his attention to the flight control tasks, leaving other tasks like navigation and communications to the copilot.

(g) (U) With expanded missions and the advanced capabilities expected in the LHX, it would be advantageous to the overall success of the mission if the pilot of the aircraft could spend less attention on the flight control task and more attention on other combat functions. From the human factors point of view, it appears to be a minimum requirement when considering a single-crew LHX. From the limited testing conducted so far, the evidence indicates the fly-by-light and/or fly-by-wire concept of flight control has the potential to relieve the pilot from some of the flight control effort. That potential for improved handling qualities, automatic stabilization, and flight of the aircraft should be pursued. The use of a side-arm controller to replace the three separate controls now found in helicopters also has some advantages with respect to the reduction of stress and fatigue caused by the aviator's "slouched" position, the removal of visual restrictions between the aviator and the controls and displays, and the increased flexibility afforded the crewstation designer regarding the placement of displays. In addition, the integration of the control functions into less than three separate controllers should relieve the pilot from having both hands and feet simultaneously occupied in flying the aircraft. The question concerning how many of the three control functions should be placed on a single side-arm controller remains unanswered. Although the aviator's physical workload may be less under the side-arm controller concept, the cognitive and mental workload associated with that task may very well be increased. Additional investigation through simulation and flight testing are needed to address that concern.

(5) (U) System status monitoring.

(a) (U) The monitoring of the health and status of various aircraft systems (engine, transmission, electrical system, hydraulics, fuel flow) is considered to be an essential task to assure safe flight. In today's aircraft, that information is displayed in the crewstation, on the instrument panel and center console, through the use of as many as 14 round dials and gauges for quantitative information, supplemented by over 20 discrete lights and audio tones.

(b) (U) Quantitative information is displayed when the conditions involved are dynamic and require continuous monitoring. Examples of this type of information would include the amount of fuel left in the aircraft fuel tanks, engine pressures or temperatures, and electrical system voltage levels. Continuously displayed quantitative data provides the aviator with trend information concerning the parameters monitored. Trend information is important to the aircrew because it permits them to assess the overall system status, detect impending adverse conditions, evaluate how rapidly the adverse condition is progressing, and take action to stop or reverse the trend.

(c) (U) Discrete information displays are the type that provide binary information that indicates if the state of the system monitored is good or bad. The master caution light is a good example of that type of display. When the light is not on, it indicates the systems monitored are operating within a "safe" condition. When the light is on, it indicates a problem that requires the aviator's attention. It does not provide quantitative or trend information.

(d) (U) Both the quantitative and discrete displays convey needed information, but there is some concern as to how well that information is detected and used by the aircrew. Several studies have shown that, during terrain flight, the attention of each member of a two-man aircrew is virtually consumed by the tasks of flight control, terrain and obstacle avoidance, and navigation. Less than 10 percent of their time is devoted to monitoring other flight instruments, communication controls, and system status displays. Add to this the tasks of observing enemy movements, target detection, and combat communications, and the time available for monitoring system status displays will be further decreased. Flying at night will compound the problem. During the heat of battle, the aircrew cannot afford the time required to monitor the aircraft system status; on the other hand, if that task is not accomplished, it could lead to disastrous results.

(e) (U) The timely acquisition of both quantitative and discrete system status information and the decisions based on that information are important to the LHX survivability. How well that is accomplished is dependent on the information being available and the aircrew having sufficient time to monitor the displays to obtain the information quickly. This presents a considerable challenge in a two-crew aircraft where one crewmember may be able to devote some of his time to monitoring the system status. In a single-crew LHX, the need to relieve the aviator of this task is more critical.

(f) (U) The data related to the status or condition of aircraft subsystems is demand-type information. Aviators require that type of information to assure them that the aircraft systems are operating properly and to warn of a possible impending failure. Under normal operating conditions, some status information is not necessarily needed except to build the aviator's confidence. The demand for system status information becomes critical when the systems being monitored are not operating well and could result in degrading of the mission or losing the aircraft.

(g) (U) Considering the limited time available for system status monitoring and the type instruments used in most fielded aircraft, it is very probable that the aircrew may not detect a rapidly developing out-of-tolerance condition when flying NOE. First of all, NOE flying requires that most of the crew's attention be focused outside the cockpit. Second, humans by nature are not good monitors of relatively slow-changing displayed information. Aviators tend to rapidly scan such displays but do not always obtain the necessary information from them. During a 5-day aviator fatigue study in a UH-1 simulator, it took the flight crew from a few seconds to 20 minutes to notice the engine oil temperature had reached a point well above the red line. Another aspect of the problem with system-monitoring displays is the large amount of panel space required for those devices. The system-monitoring displays occupy a disproportionate amount of panel space compared to the amount of time the pilot views these displays.

(h) (U) The ideal aircraft system status-monitoring system should be one that is capable of sensing a changing trend in system status, determining if that trend is within or approaching tolerance limits, and then warning the crewmembers when the system status is approaching an adverse condition that requires their attention. The aircrew can then assess the problem and implement corrective procedures when needed. From a human factors engineering perspective, system status monitoring is a prime candidate for automation. Monitoring is a task that humans do not do well, while computers can perform that task extremely well.

(i) (U) The concept of system status management by exception is quite appropriate for the LHX. A computerized monitoring system could maintain constant vigilance, perform trend analysis, diagnose abnormalities, and provide the aviator with the information he requires or desires. If the systems are functioning within tolerance limits, the aircrew need not be provided any information unless they specifically ask for it. When a condition demanding the aviator's attention arises, critical information the aircrew needs for that particular situation could be provided on the crewstation displays.

(j) (U) A concern from the human factors engineering standpoint is the implementation of the concept. In order for the management-by-exception system status-monitoring system to be successful on the battlefield, much attention must be devoted to determining what needs to be monitored, the tolerance limits of the various systems to be monitored, the level or depth to which the computer should diagnose the data received, and when and how to display the information to the aircrew. The recommendation for the LHX is to incorporate the management-by-exception system status-monitoring concept into that aircraft. Prior to incorporating such a system, specific tests and evaluations should be conducted to answer the concerns above and to assure the concept will, in fact, reduce crewstation workload.

(6) (U) Communication.

(a) (U) Effective and accurate communications are also critical to the successful completion of LHX combat missions. This is especially true for the SCAT version. The LHX crew must be able to effectively communicate with a large number of friendly forces. The Army 21 concept dictates a greater need for improved communications with an increasing number of other members of the combined arms team than did past conflicts. To meet this need, additional radios have been placed in aircraft crewstations. Each new addition increases the crewstation workload by increasing the number of controls and displays the aircrew must operate and monitor.

(b) (U) The impact that the addition of individually dedicated radio control display heads has on the aircraft cockpit is best described by the results of the "Advanced Scout Helicopter Man-Machine Interface (MMI) Investigation." That evaluation consisted of a review of the literature supplemented by studies conducted in a crewstation mockup using standard communication systems. The results of that evaluation suggest that 56 percent of the aircrew mission time involves some type of communications distributed across a variety of radios. If the LHX aviators are to be effective on the modern battlefield, the overall time devoted to communications needs to be reduced.

(c) (U) One method of reducing the workload associated with the communication task is to integrate the various radio controls into one panel. Such an integrated avionics control system (IACS) was developed through the Army Avionics Research and Development Activity. A similar system is utilized in the OH-58D helicopter. In these systems, the aviator uses an alphanumeric data entry keyboard along with various switches to select a number of radio functions displayed on an electronic display. These include selection of the type of radio and the specific frequency desired. In addition, the system can be used to control aircraft navigation equipment.

(d) (U) Evaluations of the IACS indicate that the time required to access a specific radio frequency when using preset frequencies was 13 percent less than with standard control heads. When used in the manual mode, the IACS was no more advantageous with respect to crew workload than the conventional method. The integrated system does, however, provide a definite reduction in the crewstation space occupied by radio control heads and concentrates the display information in a central location.

(e) (U) The evaluations conducted so far with the OH-58D indicate the control of the communication system through a multifunction keyboard is advantageous but that approach will require additional improvements if it is to be a viable option for the LHX single-crew aircraft. For example, the system requires considerable time to manually load initial data into the system during preflight. During flight, the communication task requires progressing through a number of computer-displayed pages to communicate and send target information to other aircraft and the ground. In a two-man aircraft, the second crewmember can help with this task; in a single-crew LHX, a less workload-intensive system will be a necessity.

(f) (U) Another important factor related to the efficiency of communicating between aircraft and with ground forces is the communication electronics operation instructions (CEOI). The CEOIs are classified documents that provide the aircrew with a complete listing of frequencies, call signs, and other critical communications data concerning friendly forces within their operational area. The CEOIs are updated every 24 hours with more frequent changes if the system is suspected of being compromised by enemy action. The CEOIs are rather large and bulky documents. Aviators must thumb through many pages of the document to find the specific frequency and call signs assigned to the unit they wish to contact. The use of CEOIs can consume as much of the communication task time as the tuning of the radios. One method of reducing the workload associated with CEOIs, as well as the entry of other communication and navigation information into the LHX during preflight, would be the provision of a bulk-loading device similar to an audio tape or disk that could transfer pretaped data into the LHX system computers within a few minutes.

(g) (U) Still another communication human factors area that must be considered for the LHX is speech intelligibility. Some of the information communicated by voice in today's aircraft is lost in the noise levels found within the communication equipment itself. Failure to transmit or the need to repeat information that one is trying to communicate easily results in a loss of information or delays that could have an adverse impact on the battle. The

LHX communication systems must provide a less noisy environment and greater speech intelligibility in the overall communication system. The technologies available for incorporation into the LHX appear to be capable of accomplishing that goal. The use of improved sound-canceling microphones, more acoustically efficient earcups, and control system noise suppression techniques would do much to improve the situation.

(h) (U) Another aspect of communication workload that requires attention is the transfer of targeting information to other aircraft or ground forces. In the current aircraft, most of the information is transferred by voice communications. The copilot or observer often handles that task. The results obtained so far through operational and developmental testing indicate that the airborne target handoff system (ATHS) has the capability to transmit a large volume of data in a short period of time, but one member of the dual-crew aircraft must devote considerable time to entering information into the system. The ATHS needs to become more automatic if used in the single-crew LHX.

(i) (U) From a human factors viewpoint, the crew workload and information transfer accuracy of communication systems for the LHX must be improved considerably over current systems. The LHX should use an integrated communication control system in which all radios and navigation systems can be controlled from a single device. The task of entering data into the aircraft computer system, including a full CEOI, should be automated in a user friendly way. The integrated communication display/controls must be designed to unburden the crew from the need to process through a large number of computer pages when desiring to transmit information. The noise levels in the system must be reduced and speech intelligibility must be increased to allow for a high probability that a message can be transmitted accurately the first time it is attempted. Automatic target handoff capabilities should be provided in which the information is gathered and transmitted with little crew interaction.

(7) (U) Survivability.

(a) (U) ASE will be an important factor in the success of the LHX. The threat possesses a formidable array of ground and airborne systems that can be used against Army aircraft, including the individual soldier's hand-held weapons, radar and optically guided missiles, heat-seeking sensors, ECM, attack helicopters, and fixed wing aircraft. The primary defense against many of those weapons will be threat avoidance. When complete avoidance is not possible and the LHX is detected, the next defense is to prevent the threat weapon from reaching the aircraft by using evasive maneuvers or countermeasures. The defensive techniques and methods for survivability are as varied and as numerous as the threat they are expected to encounter. Countermeasure aids fall into two major categories: detection and jamming/decoys. A capability should be available in the LHX time frame for detecting threat systems expected to be encountered on the battlefield of the future. Jammers should likewise be available for radar, lasers, and IR systems. Flares and decoys are also expected to be part of the LHX defensive system.

(b) (U) The detailed capabilities of each of those systems are covered elsewhere in the TOA. The concerns from the human factors standpoint are the ability of the aircrew to react to these devices and to take the appropriate corrective action to avoid becoming a casualty.

(c) (U) The first area to consider is complete avoidance of the threat. To accomplish this, the aircrew requires information concerning the threat type and location. Some of the information will hopefully be provided to the aircrew before starting the mission. Provisions for entering known threats into the LHX computer memory and the display of those threats on a situation awareness display, along with geographic location information, must be available to the aircrew. The aircrew can then plan their flight course around those threats. Provisions should also be made to update that information during flight through information automatically provided from other aircraft or ground systems, the onboard sensors, and manually by the aircrew. ASE detectors and countermeasures must be kept to a minimum. For the LHX to react rapidly to the threat, the automation of some countermeasures should be considered. The pilot should, however, have an override capability that allows him to control the ASE when automatic activation may be a disadvantage. For example, the LHX will only be able to carry a limited quantity of chaff and decoys. To conserve these resources, the crew should decide when and where to use them. A fully automatic system may dispense them too rapidly and at a less than optimal time.

(d) (U) The LHX will operate in a highly lethal environment of combined air and ground threats. The aircrew must, therefore, be provided with effective threat detection and countermeasures so the LHX cannot only survive on the battlefield, but stay and fight. These systems should provide a capability to detect and counter threats located completely around the aircraft, as well as below and above it. Current ASE does not always provide that full capability. For example, an air threat behind the LHX, when not radiating a detectable signal, may not be detected by the aircrew engaged in battle. ASE significantly enhances the chances for both the aircraft and crew survivability and mission success.

(e) (U) ASE hardware and software developments appear to have kept pace with most of the threat but through dedicated individual systems. The integration of the ASE for simplistic presentation to the aircrew, in a prioritized format, is essential for a single-crew aircraft. It is recommended that an analysis be conducted to determine the degree of integration necessary and to determine the most effective method for information presentation, how it should be displayed, and when it should be displayed. In addition, ASE countermeasures should be considered for automation.

(8) (U) Target acquisition/designation.

(a) (U) One of the most important combat functions of the SCAT version of the light helicopter fleet is target acquisition and engagement. A high level of automation must be incorporated into the LHX to allow the SCAT to accomplish that function. Advanced technology must be fully integrated into the crewstation to maintain the crew workload at a manageable level that will permit mission success. The current capabilities of target acquisition and engagement systems in Army aircraft are reflected in the AH-1 Cobra and AH-64 Apache attack helicopters. Those systems were designed to perform the target acquisition and engagement function in the air-to-ground role. During the attack mission, the pilot of those two-crew aircraft flies the aircraft and maneuvers it into the proper position to engage the enemy. The targeting function is assigned to the copilot/gunner who is totally occupied with the target acquisition and engagement task. The workload of both crewmembers during the attack mission is relatively high. The single-crew LHX will only become a reality if major technology advances are available to reduce the workload level of the two crewmembers down to a level that can be handled by one.

(b) (U) The sensors that are available in the Apache attack helicopters include direct view optics (DVO), day television systems (DTV), and a forward-looking infrared (FLIR) system. The DVO and television systems are used mainly during the day. The FLIR system is useful during periods of reduced visibility and at night. The target acquisition and designation systems in the Apache directly place the sensor data and aircraft weapon information on both the pilot's and copilot/gunner's display. The success of the target acquisition and engagement systems on current attack helicopters is therefore fully dependent on the combined abilities of the two-member crew.

(c) (U) The candidate sensors for the LHX include DVO, video/television sensors, IR devices, and radar. Much like the Apache, the video/television and DVO can be used during daylight. The FLIR and radar systems can be used during the day and at night. One of the major factors that will influence the overall success of the LHX target acquisition and engagement capability will be the maturity level of the various sensors needed to acquire and provide information concerning the type of target and its location on the battlefield.

(d) (U) The second part of the equation involves the methods and systems used to pass that information on to the aircrew. As mentioned earlier, the attack aircraft in the field today require a crew of two to be effective. How well the LHX target acquisition and engagement system operates is dependent on the consideration given to human factors engineering criteria and the soldier-machine interface. To reduce aviator workload and facilitate the target acquisition and engagement task, a faster, more sophisticated method of data processing and correlation must be developed for the LHX. The ideal system would be one that fully automates the target detection, acquisition, tracking, identification, and engagement tasks, and provides a capability to automatically pass target information to other members of the combined arms team. The level at which these functions can be successfully automated will significantly impact the crew size of the LHX. From the human factors viewpoint, the automatic processing of the various sensor inputs to provide a composite display which only contains the information necessary for target engagement or handoff should do much to ease the crew workload.

(e) (U) Target tracking should be automated to assist in holding the target within the FOV of the sensor and displays and to reduce pilot workload when performing that function. The systems should automatically compute target location and range with respect to the aircraft and geographic position. That information, along with target identification information, should be automatically transferred to the communication system and transmitted to other friendly forces. Expansion of the sensor visual scene through a number of FOV selections should be provided to allow the aircrew to better see and examine specific targets or points of interest. The FOV changes associated with that expansion should be as gradual as possible to allow the operator to continuously track the target.

(f) (U) Recordings of the information obtained through the sensors would provide a capability for the aircrew to only expose their aircraft for a short period of time, obtain a picture of the battlefield, return the aircraft to a safer position, and then play back the recording obtained. The full extent of this capability has not yet been evaluated, but it would assist in increasing the survivability rate of the LHX by permitting a more detailed examination of potential target data in a less vulnerable position. The recording capability would also be of considerable use to collect information during reconnaissance missions and to assess battle damage after an attack.

(g) (U) The methods for displaying the target visual information that appear to be within the LHX technology time frame are twofold: a panel-mounted display (PMD) and a helmet-mounted display (HMD). The PMD, by itself, is a poor option for a single-crew LHX because it requires the aviator to keep his head inside the crewstation. The HMD system will be a necessity for the single-crew LHX where the pilot must keep his eyes outside the crewstation as much as possible. One disadvantage of the HMD is the large variety of information the pilot needs to have on that display to fly the aircraft and to perform the targeting function. The aircrew could be easily inundated with too much information. The alternative would be a combination of PMDs and HMDs. The PMD in the crewstation could display the detailed information from the targeting system sensors individually or as an integrated composite. Portions of that information could be extracted and placed on the HMD to provide the minimum information required by the aircrew. If the system were fully automated, the aircrew would need only enough information to assure the process was operating correctly.

(h) (U) Human factors standards and handbooks provide considerable data concerning visual limitations and criteria with respect to the design of display characteristics. The major challenge for the LHX is not necessarily in that area but one of meaningful integration of the sensor inputs that will provide the aircrew the information needed without creating a workload level they are unable to cope with.

(i) (U) Target sensor systems will also be required to automatically scan for airborne targets, as well as ground targets. That capability should include a 360° target search completely around the aircraft.

(j) (U) Target acquisition and engagement in current Army attack helicopters is a two-crewmember task. For a single-crewmember LHX to effectively accomplish that mission, a major leap in sensor capabilities and the automation of many of the target acquisition and engagements must be accomplished. That automation should cover all functions from initial target detection until engagement of the target. In addition to the current activities associated with air-to-ground targeting tasks, the LHX crew must also contend with air-to-air target acquisition and engagement tasks. Based on the technology assessments presented so far, not all of the target acquisition and engagement functions can be automated, particularly target recognition. The aircrew will be expected to make the final confirmation that the target is the enemy and make the decision to engage the target. From the human factors perspective, the concept of multisensor fusion or integration and the display of the composite results have not yet been evaluated in sufficient detail to allow a valid prediction of its capabilities or limitations. A number of development efforts are underway but they are still in the early stages. Further efforts in this area are required to make a single-crew LHX a reality.

(9) (U) Aviation life support equipment (ALSE).

(a) (U) ALSE, including protective gear, also plays an important role in aircrew survival in combat. In addition to the NBC protection previously discussed, ALSE includes:

-- Protective helmets.

-- Flight suits.

-- Armor panels and vest.

-- Aircraft environmental control systems.

-- Oxygen systems.

-- Laser and nuclear eye protection.

-- Cold weather clothing.

-- Survival gear and radios.

-- Weapons.

(b) (U) The protective helmet not only contains the system by which the aircraft can communicate within and outside the crewstation, but also provides head impact protection during a crash and provides environmental noise attenuation to protect the aviator's ears. Unless the LHX is radically different from previous aircraft designs, similar protection will still be necessary. Future helmets should also include laser and nuclear flashblindness protection unless that protection can be built into the aircraft itself. Add to this the wide FOV HMDs expected in the LHX, and the helmet system becomes more complex. The LHX helmet with all the above systems and NBC protection added will be much different from present helmets. The new aircrew integrated helmet, now under development, integrates impact, noise, laser, NBC, and flashblindness protection into one helmet, but it is not addressing the HMD issue. An advanced LHX helmet development program needs to be initiated to address this issue.

(c) (U) Protective armor is another area where the LHX design could do much to alleviate the performance degradation associated with those devices. Aviators now fly with armor protective seats and armor vests. The vests are bulky and heavy and restrict aircrew movements. The LHX should consider additional armor protection as part of the aircraft so that the amount worn by the aircrew could be reduced. When it is necessary for the aircrew to wear body armor, the LHX crewstation configuration must take into consideration the restricted movements of the aviator while wearing such armor.

(d) (U) The environmental control systems, heating, and cooling ventilation in today's fleet fall far short of providing the optimal environment for the aircrew to operate in. The net result is increased aviator stress and fatigue that degrade mission effectiveness or time. Systems have been and are under development that can overcome this problem if applied to the LHX crewstation design.

(e) (U) Oxygen systems are required for the LHX to allow operations at altitudes above 10,000 feet mean sea level, such as that found in mountainous terrain. During night operations, oxygen has also been found to greatly increase night vision capabilities at a few thousand feet above sea level. Due to the logistics problems associated with bottled oxygen systems, it is recommended that the LHX have an onboard oxygen system designed into the aircraft. Such systems that are presently flying in Air Force and Navy high-performance aircraft could be adapted to the LHX for that purpose.

(f) (U) Improved flight suits, cold weather clothing, survival gear, and survival radios are all being developed under Army and tri-service programs not directly related to the LHX. Those programs should mature independently of the LHX. The LHX crewstation design must, however, take into consideration the space constraints required for that ALSE. The crewstation controls and displays must, for example, consider operation by aviators dressed in bulky cold weather clothing. When wearing survival gear, the aviator's movements will also be restricted. The LHX should, at a minimum, consider building some of the survival gear into the aircraft seat so aviators do not have to wear it on their bodies. The LHX design must also provide storage space for ALSE that must be stored on the aircraft, in flight, and on the ground when not in use.

(10) (U) Displays and controls.

(a) (U) The method in which information is displayed to the aircrew of the LHX and the controls provided to operate the mission equipment and systems are perhaps the most crucial aspect of the crewstation design. As mentioned earlier, the increased demands of the Army 21 concept, coupled with the continued addition of new and more complex systems into the helicopter crewstations, are rapidly approaching a point where crew workload or attention demands may prevent obtaining the maximum effectiveness from the aircraft capabilities. Studies have shown that when flying at terrain flight levels, particularly NOE, the pilot's visual attention concentrated outside the crewstation varies from 33 to 80 percent of the overall available time, depending on the mission profile. This leaves little time to monitor the displays and controls within the aircraft.

(b) (U) To assure success in the airland battle, aircrew workload must not be allowed to exceed a level that restricts the effective use of full aircraft capabilities. The best aircraft system available is of little use unless it can be effectively operated by the aircrew. One solution for reducing the variety and quantity of individual displays and controls is the use of a fully integrated electronic cockpit. That approach replaces the many cockpit displays, toggle switches, push buttons, rotary switches, and electromechanical meters and gauges with TV-like displays and electronic keyboard controls. The potential advantages of an integrated electronic crewstation when designed for effective human interface are:

1. (U) The capability to provide the relevant data required by the crewmembers in the most accessible panel areas of the crewstation.

2. (U) A reduction of the forward instrument panel space required for displays, thus improving the out-of-cockpit visibility.

3. (U) The use of flight computers to partially relieve the aviator's mental workload by integration of raw flight data into a form that requires less dedicated displays.

4. (U) A reduction in the weight of existing aircraft systems by combining current functions, supported by a number of black boxes, into one less bulky system.

5. (U) A reduction of the number of controls presently in the cockpit.

(c) (U) Displays, combined with the visual capabilities of the aircrew and the sensors feeding them, provide the information to support the basic mission functions of spatial orientation, flight path control, weapon delivery, survivability, navigation, and aircraft system monitoring. Each of these functions places demands on a portion of the aviator's attention during a typical LHX mission. The mission success will therefore be very dependent on the manner in which that information is presented to the aircrew and the division of the aviator's time to properly attend to each of these functions.

(d) (U) One concept for the presentation of visual information in the LHX is the use of a wide FOV panoramic display, mounted in the aircraft in front of the aviator, that would display aircraft performance information superimposed on an image of the outside world, with resolution and visual capabilities that are similar to that of the human eye. It is recognized that the technology development for such sensors and displays has not yet reached a maturity level that would allow that to occur and reportedly will not do so within the constraints, goals, and time frame of the LHX. The two visual display options that appear to be available for the LHX are helmet-mounted and panel-mounted displays. The attributes of each will be covered in more detail.

1. (U) The use of a helmet-mounted display (HMD) in the LHX that would allow the aviators to keep their eyes outside the crewstation, while simultaneously having mission information displayed on a see-through lens in front of their eyes, could provide a significant advantage when flying NOE and when acquiring and destroying targets. In both those flight modes, while performing the pilotage or a targeting task, much of the aviator's attention is concentrated on things outside the crewstation with little time to monitor displays in the crewstation. The HMD, when integrated with a head-sensing system and weapon control, would also provide a means to rapidly slew weapons and/or weapon sensors by means of head movements.

2. (U) Two of the major design criteria that need to be established for the HMD are the FOV and the field of regard (FOR). The ideal FOV and FOR for HMDs, from the human factors engineering standpoint, would approach those of the human visual system. The assessment of current technology indicates that full capability will most likely not be available for the initial fielding of the LHX; therefore, some smaller FOVs and FORs must be considered.

3. (U) There is little in the way of scientific data to establish the exact requirement, but a number of evaluations point to the need for wide FOV considerably larger than that of current systems. Flight and simulation studies, along with aviator assessments, suggest that the FOV for HMDs should be considerably greater than the 40° available in current systems.

4. (U) The estimated FOV needed for the LHX, reported in the U.S. Army Aviation Systems Command TOD, was 110° horizontal by 60° vertical. The wide FOV permits the aircrew to acquire peripheral information that can be helpful in flying the aircraft and detecting threats. Evaluations conducted in conjunction with the ongoing "LHX Virtual Cockpit" assessment, conducted by the Air Force Aerospace Medical Research Laboratory, indicate experienced Army aviators prefer a crewstation design that incorporates HMDs with a FOV that is at least 90° horizontal and 60° vertical or greater. FOV is not, however, the only factor in the ability to gain useful information from helmet-mounted visual displays.

5. (U) Other factors such as resolution, contrast, brightness, and refresh rates are involved. The wider FOV is best, given that all these other factors are constant, but this is not always the case. The LHX HMD parameters will be a compromise between a number of criteria. The FOV will therefore be determined by the capability of the technology available in the LHX time frame to provide a wide FOV while maintaining a level of image quality that enhances human and mission performance.

6. (U) The workload analyses of the Advanced Rotorcraft Technology Assessment (ARTI) program support the need for a wide FOV display for the LHX. Preliminary information from the ARTI program received to date indicates that

a 90° by 60° FOV appears to be within the realm of practicality. This area needs to receive considerable attention to assure the resultant LHX design is mission effective.

7. (U) In addition to the FOV requirement, the sensors providing information to the HMD should be slewable to provide a FOR that approaches the aviator's capabilities at movement rates commensurate with normal head movement. With such a visually coupled system, the visual content of the HMD would correspond with the aviator's head and aircraft movement. The limiting factor will again be the capability of technology to provide the maximum FOR.

8. (U) The physical location of the sensors providing information to the aircrew is also important. The sensor itself should be positioned as close to the reference action position of the crewmember's eye as possible to reduce errors in judgment concerning aircraft location. Sensors that are located at some distance from the position of the aviator's eyes require the aviator to mentally manipulate the information he sees on his display in order to react properly to that information. The net result is a requirement for increased initial training and the need to fly with the system more often to maintain an acceptable skill level.

9. (U) The reported disadvantages of the HMD from the human factors engineering viewpoint include the limited amount of information that can be placed on the display, helmet weight, connecting cables that may impede egress from the crewstation in an emergency, a lack of easy interchangeability of tailored helmets between aviators, the considerable time consumed in fitting the helmet to the individual, and the time consumed in alignment of the sensors and weapon aiming sights. All of these areas are critical and must be addressed in the LHX system design to reduce their negative impact on operational performance. A system design that allows for interchangeable helmets and display systems between individuals and between aircraft would be best.

10. (U) Panel-mounted visual displays provide a means to reduce the relatively large number of dedicated displays found in current aircraft to a few electronic displays. The information now placed on a number of individual dials and gauges could, for example, be integrated into a visual picture on one multifunction display. The major advantage of this approach, other than a reduction in space and weight, is the capability to place more visual information within the prime viewing space of the crewstation and to require less head movement on the part of the aviator to obtain that information. This is important during flight to allow the aircrew to rapidly obtain information from the crewstation displays.

(e) (U) Voice generation and audio systems offer another approach for displaying information in the crewstation. Audio cues have been used for a number of years to gain the aircrew's attention during emergency situations and to assist in the identification of flight and navigation aids. Those audio cues vary from a single tone or sound to the use of codes to identify radio signals. A synthesized voice generated by a computer, on the other hand, produces verbal messages that sound much like the human voice. It is an advanced means by which the aircraft systems can interact with the pilot while leaving his eyes free for obtaining visual information from outside the crewstation and from other displays. It is expected that a computer will be used to monitor the aircraft subsystems in the LHX. When the computer senses that a subsystem's tolerance limits have reached a level that requires pilot attention, a speech-generated signal could alert the pilot. Threat warnings could be handled in a similar manner either by speech alone or in conjunction with visual displays.

(f) (U) Speech generation technology is sufficiently advanced that it could be used in the LHX today. The use of both generated speech and audio tones have a place in the LHX crewstation display system. Speech systems have the advantage of conveying information in a human-like voice, but do consume a dedicated amount of time and only one understandable message can be conveyed at a time. The audio tones, on the other hand, may be transmitted in a shorter period of time but require the aviator to commit to memory the meaning of various coded tones. The use of generated speech or audio tones both have an additional limitation in that the human can only process a given amount of information in a short period of time. Too many speech or audio warnings, like any other warning system, could easily overload the aircrew. The advantages of both speech generation and audio tones need to be completely integrated with the visual information displays in the crewstation to provide the best transfer of information from the aircraft sensors to the human operator.

(g) (U) The effective design of the mission equipment systems controls placed in the crewstation is as important as the display system. It is through these devices that the aircrew communicates with and controls the operation of such mission equipment.

(h) (U) In the past, that function has been mainly accomplished by the use of dedicated toggle, rotary switches, and push buttons. Those options, which are still available, can be supplemented with voice activated systems, touch sensitive electronic displays, multifunction keyboards, individual push buttons, and joy sticks. Each of these systems or approaches have been evaluated on a limited basis in the laboratory but few have received complete evaluations in Army aircraft. The use of voice activated systems, for example, provides a potential that would allow the aircrew to control system functions by talking to the system. When the aviator speaks, the speech recognition system analyzes the spoken word and converts it into digital signals that can control aircraft systems. The major advantage of speech recognition is that it allows the pilot to interact with controls and displays using spoken commands without the use of his hands or feet. Potential applications of this technology include limited flight control such as "unmask" and "remasking" maneuvers, interaction with and possibly the firing of weapon systems, tuning and controlling of radios and navigation devices, and for data entry other than manual manipulation of a keyboard of switches. The above examples are but a few that speech recognition devices can support when the technology is mature enough to do so. At this time, the disadvantages of speech recognition are equally numerous. Research efforts have pointed out that speech recognition systems have problems when operating in a noisy environment such as that of a helicopter. Emotional and physical stress effects on an individual's voice have an adverse affect on the system's ability to recognize the spoken word. Speech pattern differences between individuals is a major obstacle to the practical application of the technology. Today's systems are speaker-dependent, meaning that they must be trained to recognize the input of one particular speaker at a time. The potential for speech recognition to aid in reducing workload in the crewstations is high, but researchers in this area indicate the probability of its maturity within the LHX initial development is low.

(i) (U) Multifunction keyboards also provide a potential that should be captured for the LHX. As discussed in the section on communications, a single multifunction keyboard can be used to control a variety of radios and navigation systems, thereby replacing a number of individual radio and navigation control heads. The major advantage is the reduction of space necessary in the crewstation devoted specifically to those control functions. From the human factors standpoint, the additional space provided by the use of a multifunction keyboard provides the feasibility to better place the remaining controls and displays in a position that facilitates their effective use by the aviators. Flying the aircraft with one hand while operating the multifunction keyboard may, however, present some problems. A multifunction keyboard has been used in the two-crewmember OH-58D scout helicopter but has not been evaluated in a single-crew context. This area needs to be more thoroughly evaluated.

(j) (U) The concept of the aviator keeping his hands on the controls as much as possible has received a lot of attention in the design of recently developed helicopters. That approach attempts to place all of the critical control switches on the cyclic or collective pitch grips so that the aviator can reach and operate them without moving his hands off the flight controls. Due to sensitivity of the side-arm controller, that approach may no longer be valid. It may be best not to put any system switches on the device. The aviator's free hand can then be expected to be used to operate the mission equipment and systems other than the flight controls. The location of the system controls therefore becomes an open question that requires investigation from a human factors viewpoint. This issue is of critical importance to the single crew LHX in order to maintain the crew workload at an acceptable level.

(11) (U) Conclusions/recommendations.

(a) (U) Army aviation's role in combat has increased over the years from the relatively limited use of helicopters and fixed wing aircraft for transporting soldiers and material around the battlefield and performing scout missions to one of full, close combat missions. The expanded missions, along with the increased threat capability, demanded the design and implementation of new tactics. Helicopters are now required to use terrain flight tactics to shield the aircraft from enemy detection. Flying at low levels and NOE below treetop levels is extremely demanding on the flight crew. NOE flight requires the pilot to focus most of his visual attention outside the crewstation while rapidly maneuvering the aircraft around obstacles in the flight path. Add the other crew tasks like navigation, communication, target acquisition and engagement, and monitoring of the aircraft subsystems, and the demand on the aircrew's physical and mental abilities rapidly increases. The requirement to fly and fight around the clock further compounds the problem.

(b) (U) The increasingly hostile environment Army aviators must fight in and the number and complexity of new aviation systems require a large amount of information be presented to and assimilated by the aircrew. The most essential ingredient of the design of the LHX for the future battlefield is the integration of the vast amount of information provided by the aircraft sensors into a form that can easily be interpreted and used by the aircrew.

(c) (U) The goal of a single-crewmember LHX demands an even more efficient crewstation design. The full integration of the information displays, the control techniques employed, and the capabilities and limitations of the aircrew at a level much greater than current aircraft is mandatory if that goal is to be achieved. The functions the aircrew must perform in the LHX fall into the major functional areas of flight control, navigation, communication, target acquisition and engagement, survivability, and system status monitoring. Each of these functions is of prime importance when the LHX enters combat. The inability of the aircrew to effectively perform any one of these functions could result in degraded performance and loss of mission success. From a human factors viewpoint, the following general recommendations for the integrated crewstation should receive attention:

1. (U) Flight control. An accurate automated flight control with full terrain following and terrain avoidance capability would be best, but does not appear feasible within the LHX development schedule. The LHX should, however, provide a level of automatic control and stability augmentation that reduces pilot workload and improves mission performance. A hover-hold capability should be provided along with a low-level cruise capability. Consideration should also be given to an automatic "pop-up" maneuver control. The use of side-arm controllers to replace the current flight controls now found in helicopters also has some advantages with respect to aviator physical fatigue and the removal of visual restrictions between the aviator and the aircraft displays. The question concerning how many of the control functions can effectively be placed on a single side-arm controller remains unanswered. Additional investigations are needed to address this area.

2. (U) Navigation. The LHX navigation system should, at a minimum, consist of an electronic horizontal situation display that gives the aircrew real-time accurate, spatial information concerning their own position and the position of friendly and threat forces during day, night, and adverse weather conditions. The system should allow the aircrew to rapidly obtain information from the display with minimal head-down time inside the crewstation, provide a means to automatically update the position information, and allow the aircrew the capability to annotate the display with friendly and threat information. The feasibility and potential advantages of the digital data base navigation system should be included in the LHX when that technology matures.

3. (U) Communication. The control of the numerous radios and navigation aids from a central point should be considered to free up the

crewstation space and allow more effective placement of other displays and controls. The LHX design should include an automatic data loading system that would rapidly transfer communication, navigation, threat, and other system information into the avionics computers at the beginning of the mission and would provide the capability of updating that information during flight. A communication system with less noise and better speech intelligibility needs to be developed for the LHX.

4. (U) Target acquisition and engagement. The automatic processing of information from the various target acquisition sensors, to provide a composite display which only contains the information necessary for target engagement or handoff, is recommended for the LHX. A fast method of data processing and correlation must be developed. Target lock-on and tracking should also be automated to assist in holding the target within the FOV of the sensor and displays. Video recording techniques should be employed to allow the aircrew to collect target or threat information for analysis at a later time. Sensors and related systems should be provided to automatically scan for airborne, as well as ground, targets. The ideal would be a target acquisition and engagement system with full automation of the target detection, acquisition, tracking, identification, and engagement task with the pilot as the system manager and final decision maker.

5. (U) Survivability.

a. (U) (a) ASE systems will be an important factor in the LHX. The ASE systems should have provisions for entering known threat information into the avionics computer memory, and the display of those threats along with geographic location information should be designed into the LHX. Individual threat detection devices should be integrated to form a single survivability system that rapidly provides the aircrew relevant information regarding the threat location and the countermeasure necessary to defeat the threat. The threat information must be prioritized and the threats displayed must be limited to the optimal number the aircrew can handle at one time. The information presented to the aircrew should include target position and location, as well as information concerning the appropriate defensive action the crew should take to defeat the threat.

b. (U) NBC defensive measures must be a part of the crewstation design of the LHX to allow the aircrew the option to avoid contaminated areas or to fight in them. The system design should include NBC collective protection provided through a sealed and pressurized aircraft, remote detectors to warn the aircrew of contaminated areas before they have entered the area, and point detectors to advise the air and ground crews when the exterior or interior of the aircraft has become contaminated. The capability to maintain the individual aviator at the optimal body temperature while clothed in NBC clothing should also be included. The crewstation controls and displays should be designed so that they are compatible with the aviator in full NBC gear and life support equipment. In addition, the LHX design should consider agent-resistant coatings and the application of design techniques to prevent contamination from adhering to the exterior surfaces and entering the interior subsystems of the aircraft. Provisions should also be provided for the addition of onboard decontamination devices at a later date.

6. (U) System status monitoring.

a. (U) Monitoring of the system status is a prime candidate for automation. It is recommended that the concept of system status management by exception be employed in the LHX. A computerized monitoring system could maintain constant vigilance, perform trend analysis, diagnose abnormalities, and provide the aircrew with the information needed to take the appropriate action required by the particular situation. The system should also be designed to allow the aircrew the capability to obtain information from the system when desired.

b. (U) The LHX crewstation should be designed so that the air and ground crews can effectively operate and maintain the aircraft when wearing cold weather, NBC, and survival clothing and gear. Space must be provided for the storage of ALSE. Oxygen systems should be provided for high-altitude and night missions. An LHX advanced aircrew protective helmet should be designed as an integral part of the crewstation.

c. (U) The detailed assessment of each of the nonmajor crew functions outlined above reveals a common denominator upon which the LHX mission performances and success heavily depend. The LHX sensors and systems all provide an enormous amount of mission-related information to the aircrew. The effective use of that information relies on the ability of the aircrew to mentally process the information, decide on the best course of action, and through the LHX controls, execute that action. To assure success of the LHX, information obtained from the various subsystems must be integrated and presented to the crew in a meaningful manner. The importance of the crewstation integration cannot be overemphasized.

(d) (U) This review of the major human factors engineering issues of the LHX crewstation integration concerns has indicated that the capabilities and limitations of the human must receive additional consideration. The LHX is expected to be a highly automated helicopter with the capability to provide the aircrew with information continuously. It is the integration of that information into the crewstation, along with the processing of that information by the crewmembers and the resulting control actions on the part of the aircraft that require much attention from the human factors engineering viewpoint. The human factors engineering analyses presented in the AVSCOM TOD and this TRADOC TOA, along with the preliminary results provided thus far from the ARTI program, all contribute to the assessment of the soldier-machine interface of the LHX and the enhancement of the crew's operational capabilities and the manpower, personnel, and training requirements. These preliminary efforts provide a framework for the development of the LHX but do not answer all the human factors engineering-related issues. Human factors engineering for the LHX crewstation is part of an iterative design process that must be continually reviewed and updated. The operational success of the LHX on the battlefield is dependent on that process continuing. The continued support from a number of government organizations and laboratories that deal with human-related aspects of Army aviation will be necessary to accomplish the LHX goals.

R-7. (U) CONCLUSIONS.

a. (U) The results of mission task analysis indicated that a fully automated LHX can be operated by a two-member crew without undesirable crew overloads. The single-crewmember analysis indicates that even with full automation the pilot will experience overloads during critical mission segments such as target engagement and reconnaissance. If less than a fully automated crewstation is provided, the aircrew workload can be expected to increase.

b. (U) The assessment of the crew size question from an operational standpoint highlights a number of advantages to a two-crewmember LHX. The analysis of operational concerns indicates that a two-crew LHX would be more survivable, operationally more effective, and safer to fly. The second individual in the crewstation should reduce fatigue and stress and provide considerable flexibility in mission performance and growth.

c. (U) The HF/MMI assessment of the LHX and the related crew size issue indicates that a considerable amount of automation will be required in either a one- or two-crewmember aircraft. The data available at this time indicates that from an operational effectiveness standpoint the single-crew LHX presents a high risk with respect to the HF/MMI. The two-crew LHX would therefore be the prudent approach in meeting the Army's future combat needs. If the goal of a single-crew LHX is to be reached, considerable effort must be expended on a number of factors including technology maturity, operational effectiveness, and the level of mission equipment, and the controls and display integration required for the LHX.

d. (U) The following automation functions are considered critical to the crewstation design, particularly if the goal of a single-crew LHX is to be accomplished:

-- Voice interactive systems.

-- Automatic navigation.

-- Automatic target detection, acquisition, tracking, and recognition.

-- Automatic threat analysis.

-- Automatic threat management.

-- Terrain following (TF)/terrain avoidance (TA).

-- Levels of TF/TA.

-- Integrated fire and flight control.

-- Integrated flight engine control.

-- Integrated flight path control.

-- Wide FOV HMDs.

-- Artificial intelligence concepts.

A pictorial and verbal description of each of these required technologies is shown in figures R-17 through R-28. The level of maturity of each of these technologies will have a definitive influence on the actual capabilities of the LHX. That relationship is shown in figure R-29.

e. (U) A major question for the success of the LHX is whether or not the above technologies will be available and mature enough to reduce the crew workload in a single-pilot LHX to a manageable level within the LHX full-scale development schedule and program goals. The ARTI program and crew complement simulation, when completed, will hopefully provide additional information to answer that question.

R-8. (U) RECOMMENDATIONS.

a. (U) The automation functions, mission equipment, survivability, and NBC systems recommended in the various sections of this report be integrated into the LHX aircraft design.

b. (U) The HF/MMI analysis presented be expanded and updated as new information becomes available from the ARTI and other R&D programs.

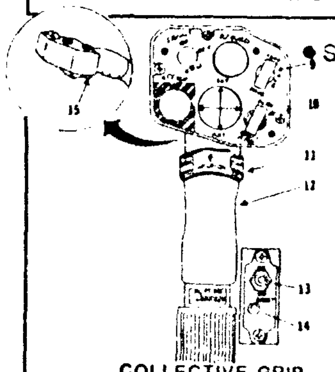
c. (U) The crew size decision remain open until the ARTI program and the government crew size simulation assessment are fully completed and analyzed.

d. (U) If the critical technologies outlined in this section and the rest of the TOA are not sufficiently mature and available within the LHX program goals and schedule, consideration be given to the initial design of a two-crewmember LHX with a program to develop the needed technologies that would allow the transition to a single-place LHX at some future date.

VOICE COMMAND - ALLOWS HANDS ON/HEADS UP OPERATIONS

TODAY - APPROACHING LIMITS OF HANDS-ON CONTROLLERS

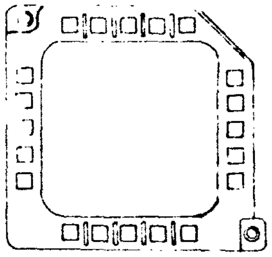
- SIDESTICK CONTROLLER:



COLLECTIVE GRIP

PILOT CYCLIC GRIP

- MULTIFUNCTION DISPLAY:
  - ✓ 20 BUTTONS
  - ✓ 60+FUNCTIONS



TOMORROW - VOICE INTERACTIVE CONTROL AUGMENTS HANDS-ON CONTROL

- FUNCTIONS:
  - SENSOR CONTROL
    - ✓ RADAR, FLIR/LASER....
  - STORES MANAGEMENT
    - ✓ WEAPONS SELECT, FUZING...
  - FLIGHT/FIRE CONTROL MODES
  - DEFENSIVE SYSTEMS OPERATION
    - ✓ CHAFF, FLARES....

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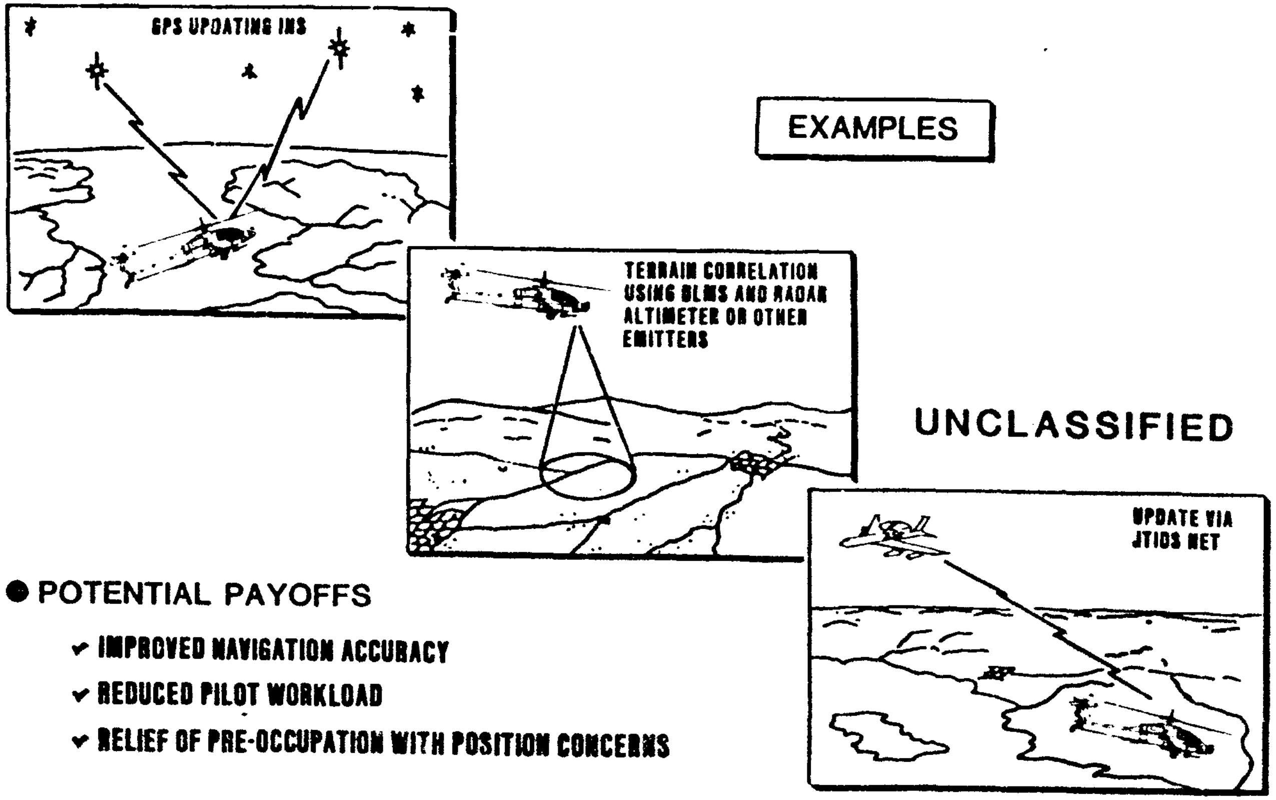
VOICE COMMAND TECHNOLOGY ALLOWS HANDS ON/HEAD UP OPERATION

Figure R-17. (U) Voice command--allows hands-on/heads-up operations.

AUTOMATIC NAVIGATION

DEFINITION – AUTOMATIC PRESENT POSITION DETERMINATION AND UPDATE

EXAMPLES



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- POTENTIAL PAYOFFS
  - ✓ **IMPROVED NAVIGATION ACCURACY**
  - ✓ **REDUCED PILOT WORKLOAD**
  - ✓ **RELIEF OF PRE-OCCUPATION WITH POSITION CONCERNS**

AUTOMATIC NAVIGATION/PRESENT POSITION UPDATE TECHNOLOGIES

Figure R-18. (U) Automatic navigation.

AUTOMATIC TARGET RECOGNITION

DEFINITION

- SINGLE SENSOR - DETECTS TARGETS IN CLUTTER
- MULTI-SENSOR - CORRELATES DATA TO INCREASE CONFIDENCE IN THREAT IDENTIFICATION INCLUDING "ALIVE" OR "DEAD"

APPLICATION

- REDUCES PILOT DECISION MAKING TASK IN POSITIVELY IDENTIFYING TARGETS
- AIDS PILOT IN SELECTING REAL TARGETS

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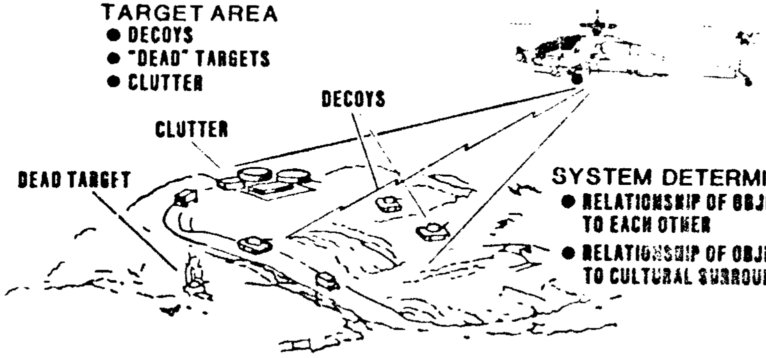
TARGET AREA
- DECOYS
- "DEAD" TARGETS
- CLUTTER



A/C SENSORS DISCRIMINATE ACTUAL TARGET FROM DECOYS, CLUTTER, DEAD TGTS. SENSORS EXAMINE SELECTED OBJECTS FOR TARGET CHARACTERISTICS

SYSTEM DETERMINES:
- RELATIONSHIP OF OBJECTS TO EACH OTHER
- RELATIONSHIP OF OBJECTS TO CULTURAL SURROUNDINGS

SINGLE SENSORS CANNOT SEPARATE REAL TARGET FROM DECOYS, CLUTTER, DEAD TARGETS, MUST HAVE MULTIPLE SENSOR TO MAKE CORRELATION
- FLIR CANNOT DISCRIMINATE METAL DECOYS WITH ELECTRIC HEATERS
- CO_2 LASER CANNOT DISCRIMINATE INFLATED DECOYS
  - FLIR AND MM WAVE CAN
- CO_2 LASER CAN DETECT ENGINE RUNNING

SUPPORTING TECHNOLOGIES

- FLIR
- CO_2 LASER
- ELECTRONIC COUNTER MEASURES (ECM)
- MILLIMETER WAVE RADAR
- RECOGNITION/IDENTIFICATION ALGORITHMS IN HIGH SPEED COMPUTERS

AUTOMATIC TARGET RECOGNITION TECHNOLOGY

Figure R-19. (U) Automatic target recognition.

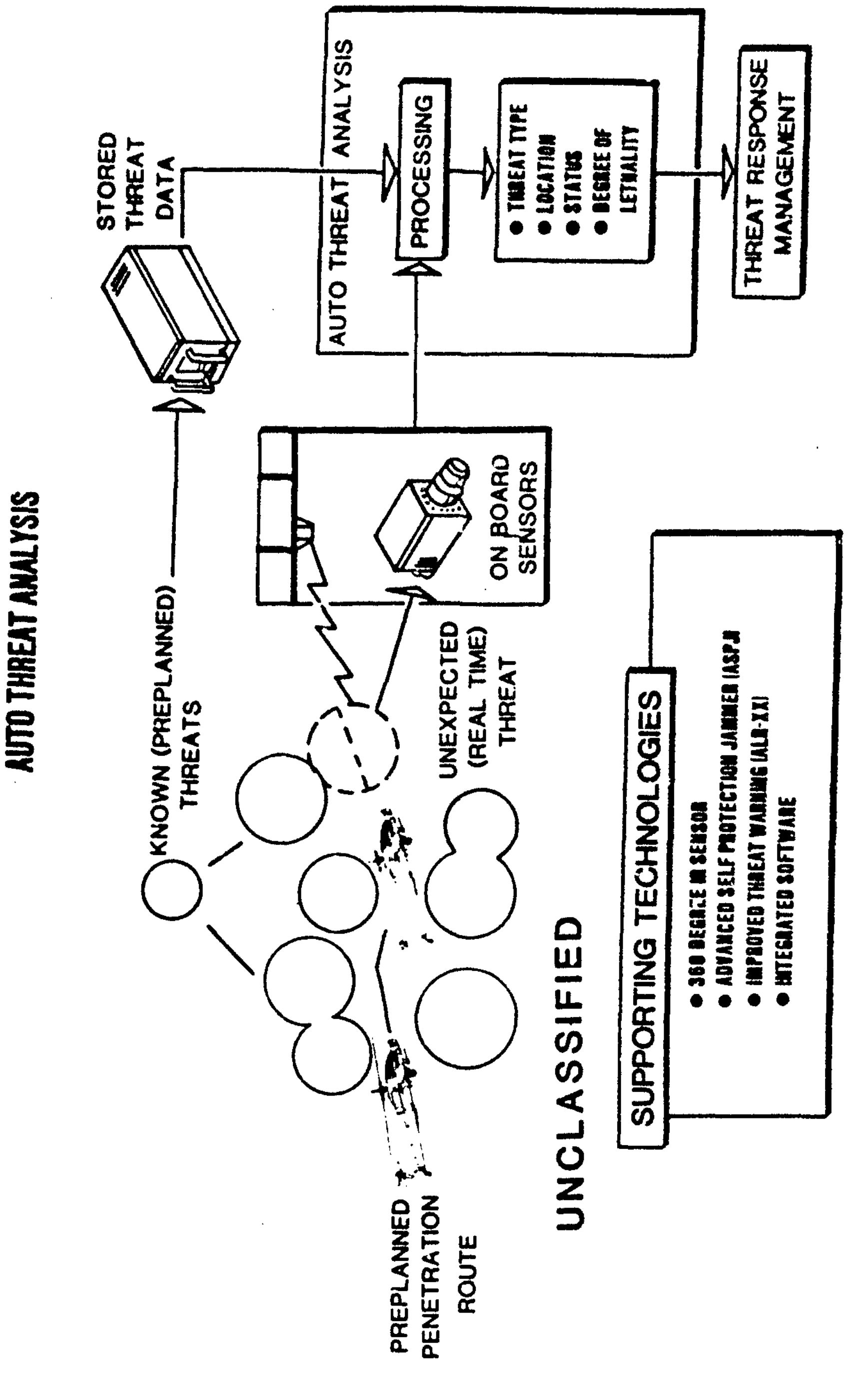
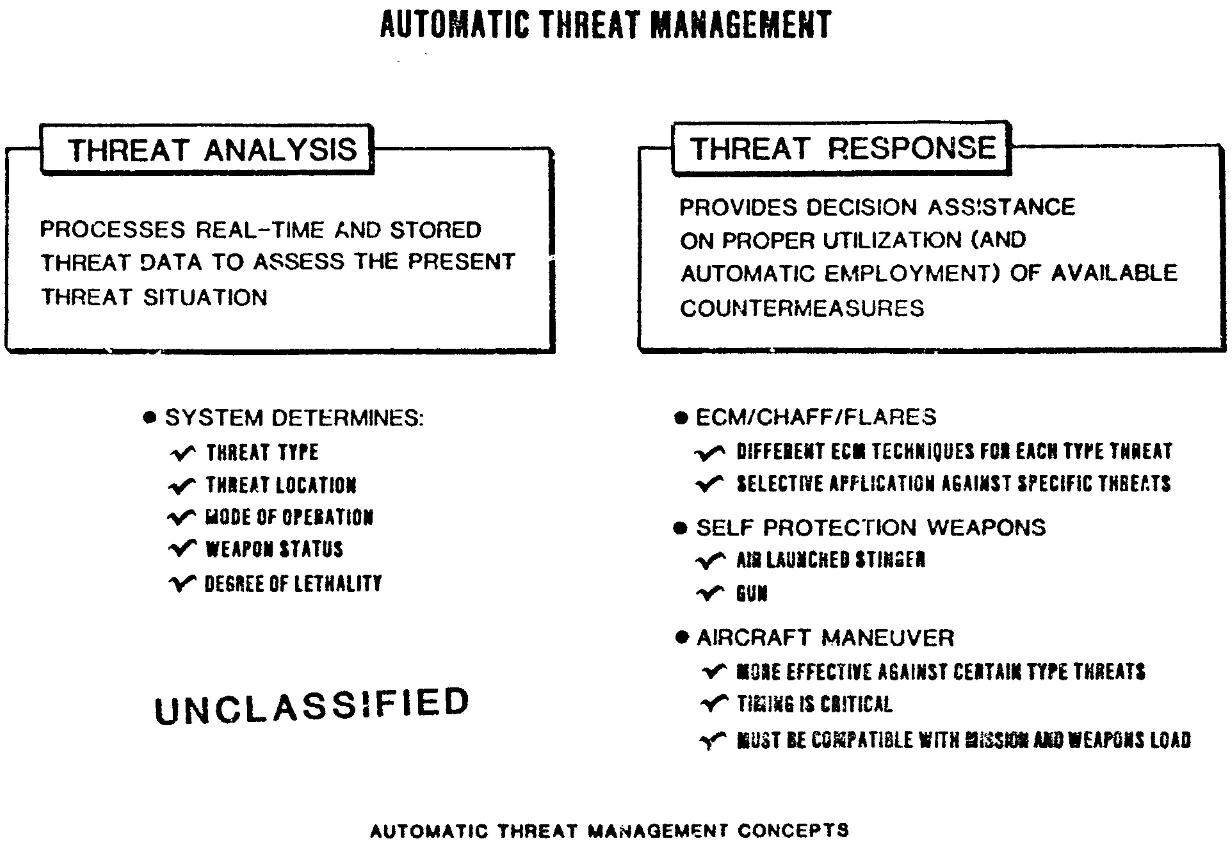


Figure R-20. (U) Automatic threat analysis.



AUTOMATIC THREAT MANAGEMENT

THREAT ANALYSIS

PROCESSES REAL-TIME AND STORED THREAT DATA TO ASSESS THE PRESENT THREAT SITUATION

- SYSTEM DETERMINES:
  - ✓ THREAT TYPE
  - ✓ THREAT LOCATION
  - ✓ MODE OF OPERATION
  - ✓ WEAPON STATUS
  - ✓ DEGREE OF LETHALITY

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THREAT RESPONSE

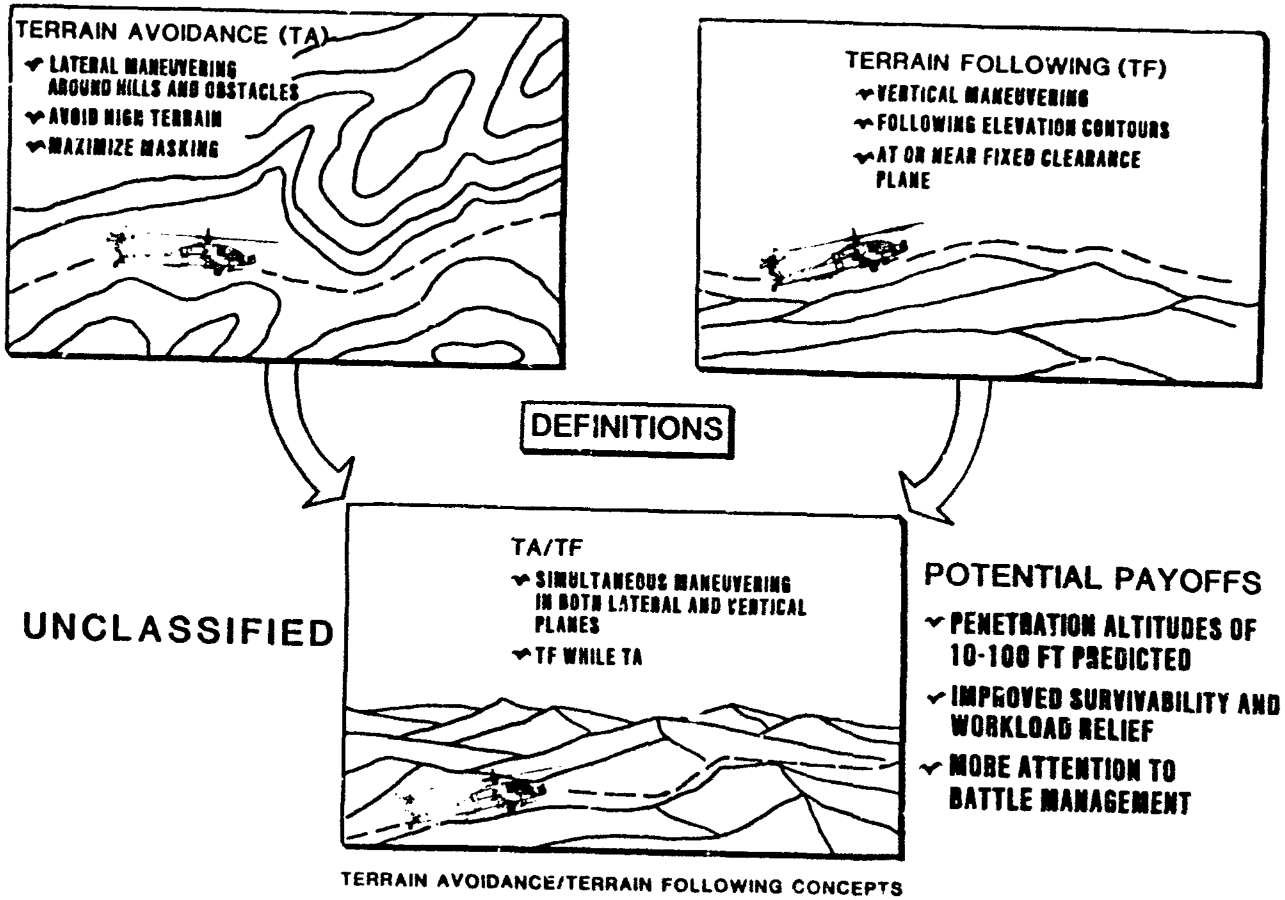
PROVIDES DECISION ASSISTANCE ON PROPER UTILIZATION (AND AUTOMATIC EMPLOYMENT) OF AVAILABLE COUNTERMEASURES

- ECM/CHAFF/FLARES
  - ✓ DIFFERENT ECM TECHNIQUES FOR EACH TYPE THREAT
  - ✓ SELECTIVE APPLICATION AGAINST SPECIFIC THREATS
- SELF PROTECTION WEAPONS
  - ✓ AIR LAUNCHED STINGER
  - ✓ GUN
- AIRCRAFT MANEUVER
  - ✓ MORE EFFECTIVE AGAINST CERTAIN TYPE THREATS
  - ✓ TIMING IS CRITICAL
  - ✓ MUST BE COMPATIBLE WITH MISSION AND WEAPONS LOAD

AUTOMATIC THREAT MANAGEMENT CONCEPTS

Figure R-21. (U) Automatic threat management.

TERRAIN AVOIDANCE / TERRAIN FOLLOWING



TERRAIN AVOIDANCE (TA)
- ✓ LATERAL MANEUVERING AROUND HILLS AND OBSTACLES
- ✓ AVOID HIGH TERRAIN
- ✓ MAXIMIZE MASKING

TERRAIN FOLLOWING (TF)
- ✓ VERTICAL MANEUVERING
- ✓ FOLLOWING ELEVATION CONTOURS
- ✓ AT OR NEAR FIXED CLEARANCE PLANE

DEFINITIONS

TA/TF
- ✓ SIMULTANEOUS MANEUVERING IN BOTH LATERAL AND VERTICAL PLANES
- ✓ TF WHILE TA

POTENTIAL PAYOFFS
- ✓ PENETRATION ALTITUDES OF 10-100 FT PREDICTED
- ✓ IMPROVED SURVIVABILITY AND WORKLOAD RELIEF
- ✓ MORE ATTENTION TO BATTLE MANAGEMENT

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TERRAIN AVOIDANCE/TERRAIN FOLLOWING CONCEPTS

Figure R-22. (U) Terrain avoidance (TA)/terrain following (TF).

LEVELS OF TA/ TF CAPABILITY

● MANUAL
- FLY VIA OUTSIDE SCENE (NAV FLIR ON HMD IN NIGHT VFR)
- FLY VIA STEERING COMMANDS

● AUTOMATIC
- AUTO, LATERAL AND/OR VERTICAL FLIGHT
- INTEGRATED DISPLAYS
- OVERRIDE CAPABILITY

● COVERT
- PERFORMS LIKE AUTO
- EMPLOYS MULTIPLE SENSORS
- DECREASES EMISSION LEVELS

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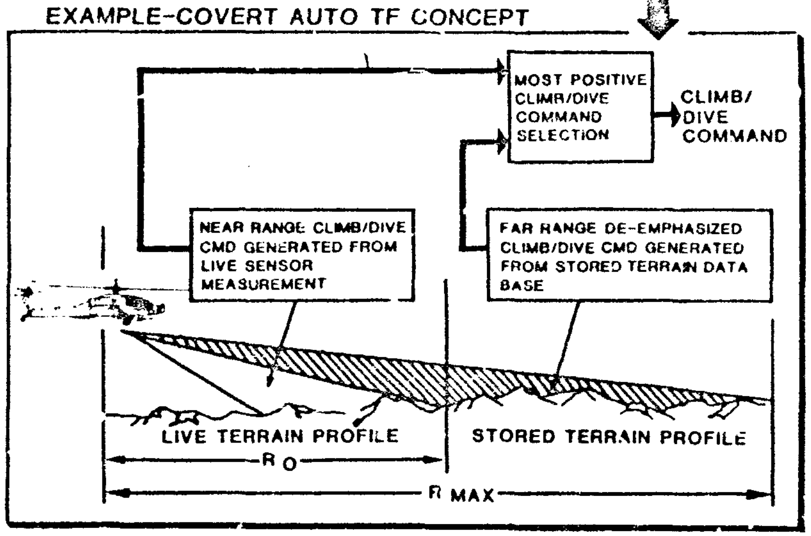
SUPPORTING TECHNOLOGIES

- **DIGITAL LAND MASS SYSTEM (TERRAIN CONTOURS AND CULTURAL FEATURES STORED IN COMPUTERS)**
- **MILLIMETER WAVE RADAR**
- **CO_2 LASERS FOR WIRES**

EXAMPLE–COVERT AUTO TF CONCEPT



LEVELS OF TA/TF CAPABILITY

Figure R-23. (U) Levels of TA/TF capability.

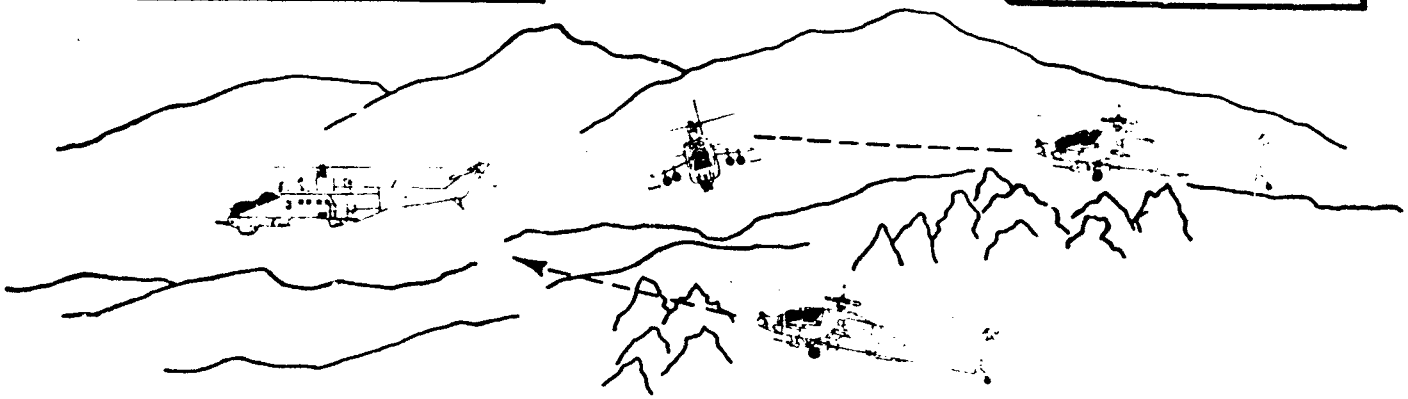
INTEGRATED FIRE AND FLIGHT CONTROL

DEFINITION

- AUTOMATIC FIRE CONTROL
- PREPLANNED FIRE CONTROL SOLUTION
  - GUNS
  - MISSILES

APPLICATION

- REDUCES PILOT TASK LOADING
- ALLOWS TARGET ENGAGEMENT
- TIME LINE REDUCTION



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- CANNON, ROCKETS, MISSILES
- AIR - TO - GROUND
- AIR - TO - AIR

Figure R-24. (U) Integrated fire and flight control.

INTEGRATED FLIGHT ENGINE CONTROL

DEFINITION

- FLIGHT AND ENGINE CONTROL COUPLING TO PROVIDE:
  - AUTOMATIC POWER MANAGEMENT
  - SPEED CONTROL

APPLICATION

- REDUCES PILOT TASKING BY AUTOMATICALLY ADJUSTING FLIGHT CONTROL SURFACES, AND ENGINE POSITIONS TO MAINTAIN DESIRED SPEED
- INCREASES FUEL EFFICIENCY AND EXTENDS RANGE

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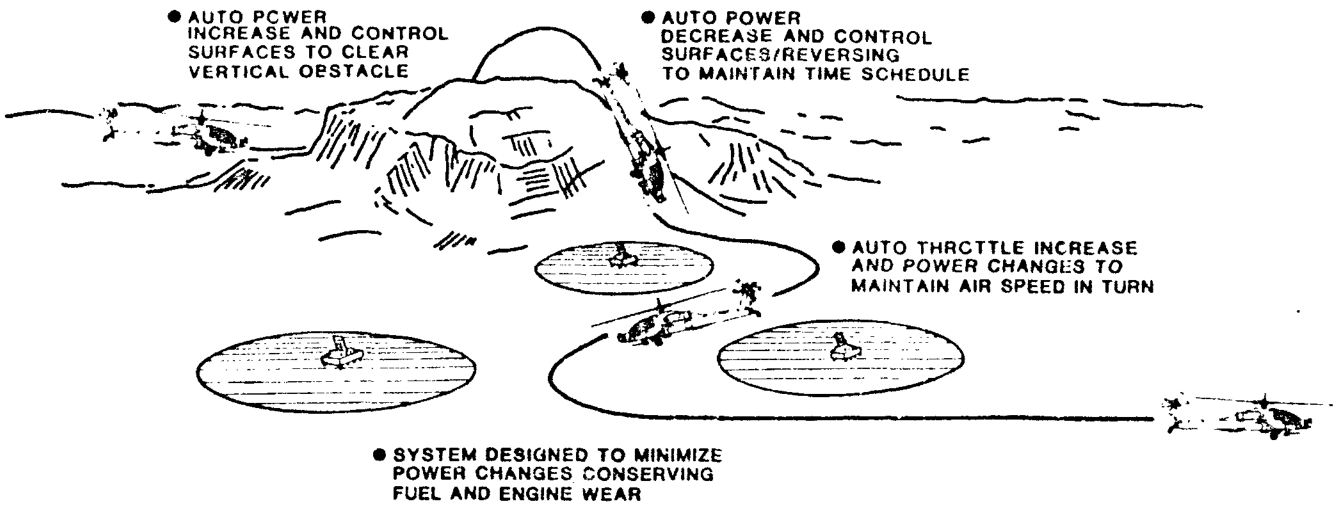

- AUTO POWER INCREASE AND CONTROL SURFACES TO CLEAR VERTICAL OBSTACLE
- AUTO POWER DECREASE AND CONTROL SURFACES/REVERSING TO MAINTAIN TIME SCHEDULE
- AUTO THROTTLE INCREASE AND POWER CHANGES TO MAINTAIN AIR SPEED IN TURN
- SYSTEM DESIGNED TO MINIMIZE POWER CHANGES CONSERVING FUEL AND ENGINE WEAR

INTEGRATED FLIGHT ENGINE CONTROL

Figure R-25. (U) Integrated flight engine control.

INTEGRATED FLIGHT PATH CONTROL

DEFINITION

- FLIGHT CONTROL COUPLING TO PROVIDE:
  - THREAT AVOIDANCE FLIGHT PATHS
  - TARGET REDIRECTS

APPLICATION

- PROVIDES REAL TIME "HIGHEST P_S" FLIGHT PATH FOR THREATS
- AIDS PILOT DECISION TASK
- PROVIDES AUTOMATIC TIME OF ARRIVAL AND FUEL USAGE ESTIMATES

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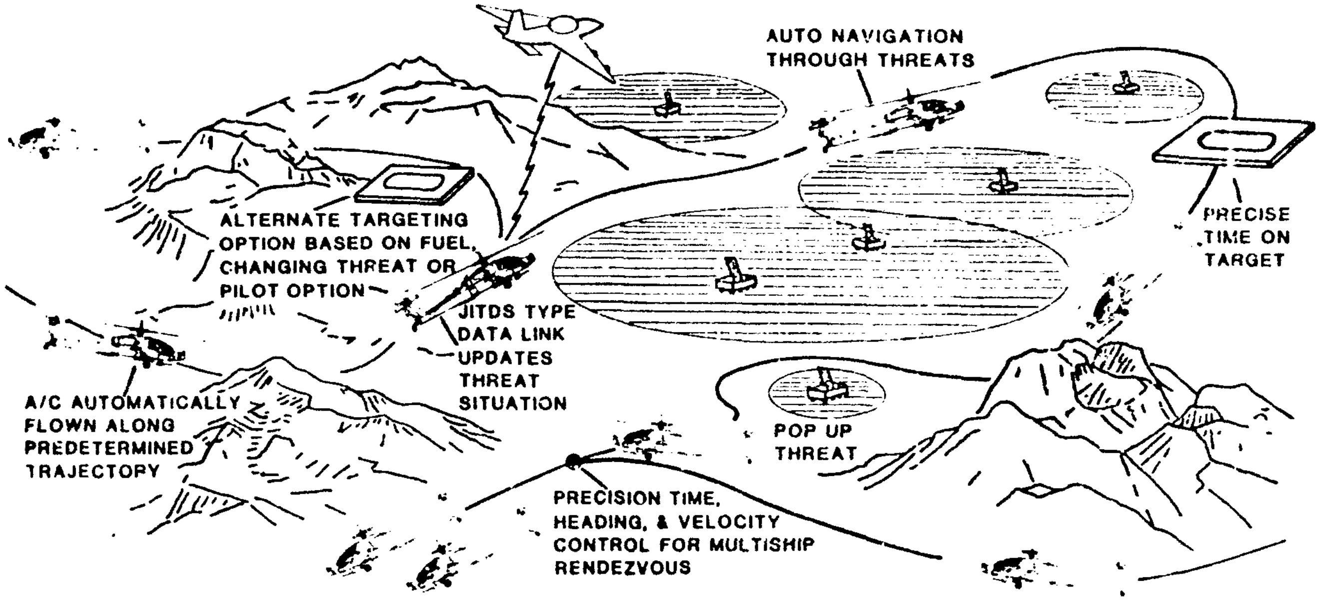


INTEGRATED FLIGHT PATH CONTROL

Figure R-26. (U) Integrated flight path control.

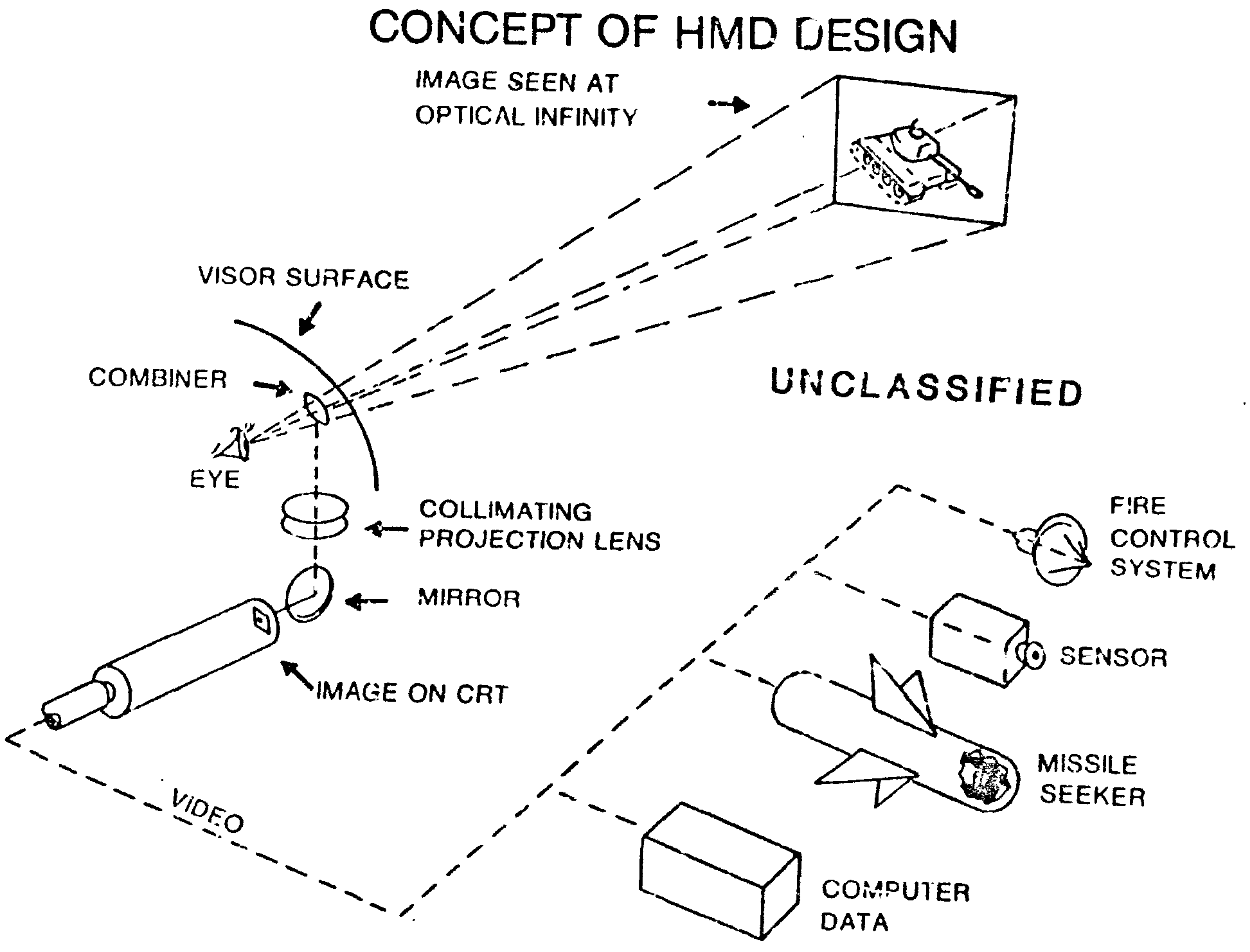
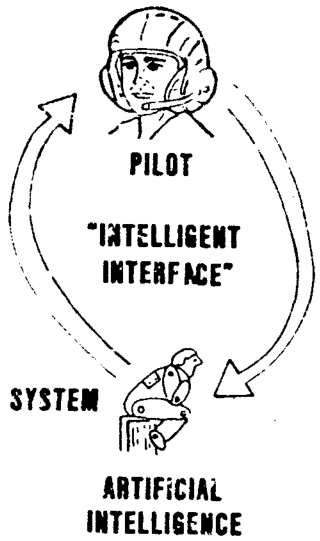


Figure R-27. (U) Concept of HMD design.

INTELLIGENT INTERFACE BETWEEN THE PILOT AND HIS AUTOMATED FUNCTIONS

- TARGET RECOGNITION
- FIRE CONTROL
- ELECTRONIC COUNTERMEASURES



- NAVIGATION
- COMMUNICATION
- SITUATION AWARENESS

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SUPPORTING TECHNOLOGIES

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- MAP DISPLAYS
- PICTORIAL DISPLAY CAPABILITIES
- VHSIC
- SENSOR FUSION
- INTEGRATED SOFTWARE
- ARTIFICIAL INTELLIGENCE
- VOICE INTERACTIVE SYSTEMS

Figure R-28. (U) Intelligence interface between the pilot and his automated functions.

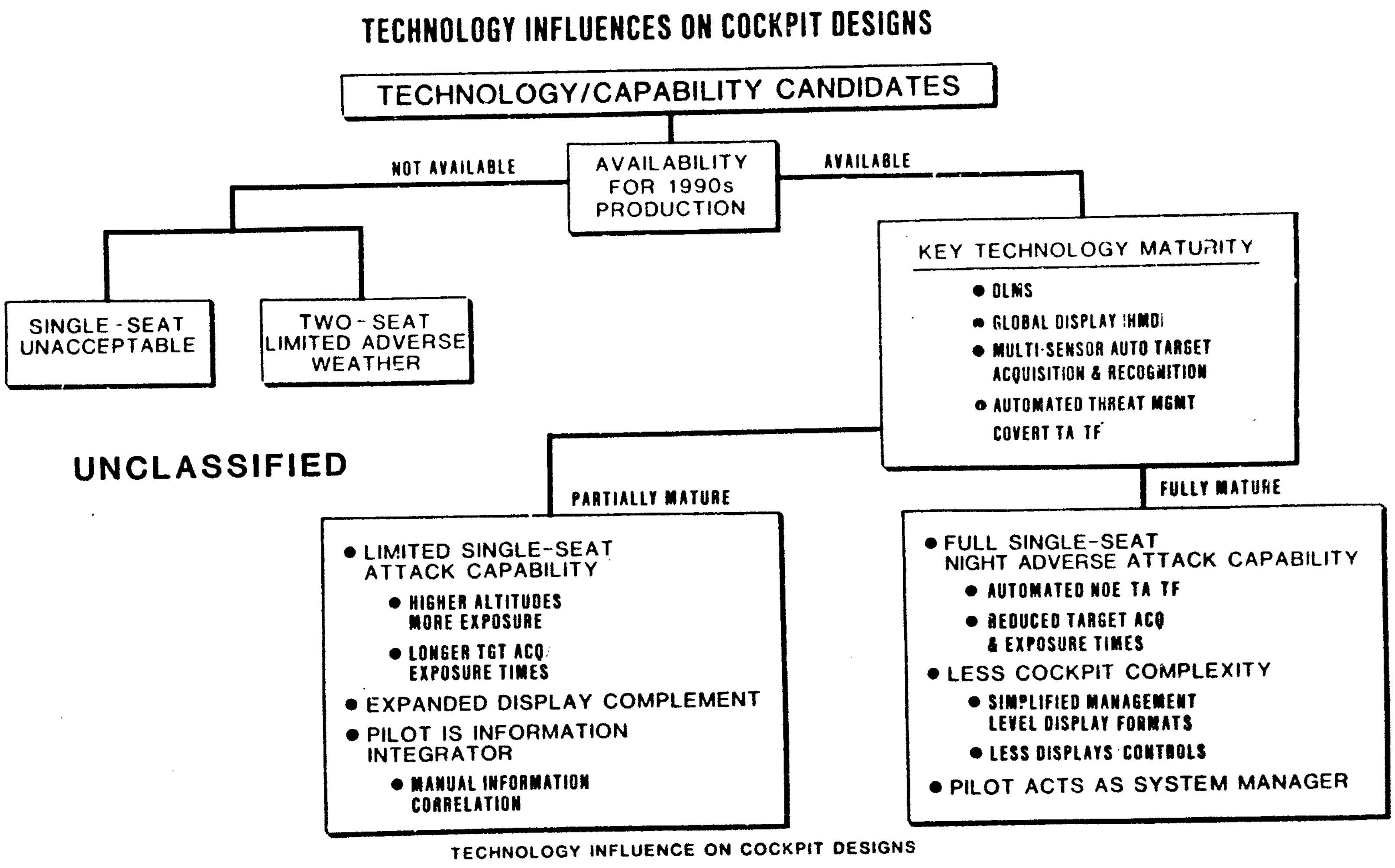

Figure R-29. (U) Technology influences on cockpit designs.

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ANNEX R-1

PROJECTIVE APPLICATION OF THE SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE TO ADVANCED HELICOPTER CREW SYSTEM DESIGNS

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Annex I to Appendix R

PROJECTIVE APPLICATION OF THE SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE TO ADVANCED HELICOPTER CREW SYSTEM DESIGNS

R-I-1. The report, "Projective Application of the Subjective Workload Assessment Technique to Advanced Helicopter Crew System Designs" is reproduced on the following pages. The report was first published by the Aerospace Medical Division of the Air Force Aerospace Medical Research Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio in December 1984.

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AFAMRL-TR-85-014

PROJECTIVE APPLICATION OF THE SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE TO ADVANCED HELICOPTER CREW SYSTEM DESIGNS

Gilbert G. Kuperman

AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY

December 1984

AIR FORCE AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
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A projective version of the AFAMRL-developed Subjective Workload Assessment Technique was applied in the evaluation of five conceptual crewstation concepts for an advanced light scout/attack helicopter. Each concept was based on a distinct level of virtual panoramic display technology (head-up display, monocular helmet-mounted display, medium and wide field-of-view binocular helmet-mounted displays, and a cabin-mounted projection display system). The mission equipment package for the weapon system was analyzed in order to identify information sources for in-cockpit display. A composite mission scenario was synthesized and six mission segments (cruise, pre-FLOT, penetration, approach to battle position, air-to-ground attack, and air-to-air attack) were selected as points at which to collect workload estimates. The six mission segments were found to be significantly different from each other ($p \leq 0.01$), and the five crew system concepts were found to be significantly different from each other ($p \leq 0.01$). There was no significant interaction

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PREFACE

The research reported in this document was performed by the Visual Display Systems Branch, Human Engineering Division, Air Force Aerospace Medical Research Laboratory (AFAMRL/HEA). The effort was accomplished under Work Unit 7184-11-45, "Display Requirements for Tactical Night Systems." The research was conducted in support of a Memorandum of Agreement between the AFAMRL and the U.S. Army Aviation Systems Command (AVSCOM) titled "Technology Assessment Study: Virtual Cockpit for the LHX."

Special thanks are due to Ms. Debra Warner of the MacAulay-Brown Company, Dayton, Ohio, and to Mr. Johnathan Greene of Systems Research Laboratories, Inc. (SRL), Dayton, Ohio, who very ably assisted in preparing for and conducting the field data collection portion of the effort; and to Ms. Denise Wilson, also of SRL, who provided great assistance in preparing the review of the workload measurement literature.

The personnel of the U.S. Army Aviation Center, Fort Rucker, Alabama, who participated as subjects in the workload prediction experiment must be acknowledged with sincerest gratitude. Their enthusiastic professionalism and highly motivated support reflect great credit on that organization.

SUMMARY

This report deals with conceptual crewstation designs for an advanced scout/attack helicopter. A composite mission is developed and six alternative crewstations are evaluated in terms of both predicted workload and pilot opinion data. The two most promising crew interface concepts (a wide field-of-view, binocular helmet-mounted display and a cockpit-mounted projection system) are recommended for development.

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GLOSSARY

AAA	Antiaircraft artillery
A/A	Air-to-air
AAH	Advanced attack helicopter (AH-64 APACHE)
A/C	Aircraft
ACAP	Advanced composites aircraft program
ACP	Air control point
ADA	DoD standard higher-order computer language
ADA	Air defense artillery
ADAS	Army digital avionics system
ADF	Attitude/direction finding
ADI	Attitude direction indicator
ADOCS	Advanced digital optical control system
AFAMRL	Air Force Aerospace Medical Research Laboratory
A/G	Air-to-ground
AHIP	Advanced Helicopter Integration Program (OH-58D/KIOWA)
AM	Amplitude modulation
APC	Armored personnel carrier
ARTI	Advanced Rotorcraft Technology Integration
ASE	Airborne survivability equipment (ECM/ECCM)
ATGM	Antitank guided missile
ATHS	Airborne target hand-off system
ATR	Automatic target recognizer
AVSCOM	(Army) Aviation Systems Command
AWACS	Airborne warning and control system
BANDIT	Confirmed enemy aircraft
B.P.	Battle position

GLOSSARY (continued)

C^3I	Command/control/communications/intelligence
CELL	A group of aircraft performing a common mission
CEP	Circular error probability
CNI	Communications/navigation/intelligence
Comm	Communications
COMSEC	Communications security
CRT	Cathode-ray tube
DADS	Digital audio distribution system
DEW	Directed energy weapon (e.g., laser)
EADI	Electronic attitude direction indicator
EHSI	Electronic horizontal situation indicator
EO	Electro-optical
EOTADS	Electro-optical target acquisition and designation system (LLTV and FLIR)
ECM	Electronic countermeasures
ECCM	Electronic counter-countermeasures
ETA	Expected time of arrival
ETE	Expected time of engagement
EW	Electronic warfare
FARP	Forward arming and refueling point
FEBA	Forward edge of battle area
FLIR	Forward-looking infrared
FLOT	Forward line of troops
FM	Frequency modulation
FOR	Field of regard
FOV	Field of view

GLOSSARY (continued)

FST	Future Soviet tank
GPS	Global positioning system
H	Horizontal
HAVE QUICK	Secure UHF communications capability
HELLFIRE	Air-to-ground missile
HF	High frequency
HIND	Soviet A/G attack helicopter
HMD	Helmet-mounted display
HMS	Helmet-mount sight
HOGE	Hover out of ground effect
HQ	HAVE QUICK
HUD	Head-up display
ICNIA	Integrated comm/nav/ident avionics
IDENT	Identification
IFF	Identification friend or foe
IFFN	Identification friend, foe, or neutral
IMFK	Integrated multifunction keyboard
IR	Infrared
IRS	Inertial reference system
IRST	Infrared search and track
JTIDS	Joint Tactical Information Distribution System
KM	Kilometer(s)
KTS	Knots; nautical miles per hour
LD	Laser designator
LD/R	Laser designation/ranging system
LHX	Lightweight helicopter family

GLOSSARY (continued)

LLTV	Low light-level television
LOC	Lines(s) of communication
LRF/D	Laser rangefinder and designator
LWR	Laser warning receiver
MEP	Mission equipment package
MFD	Multifunction display
MFPK	Multifunction programmable keyboard (IMFK)
MMI	Man/machine interface
MMW	Millimeter wave (radar)
NATO	North Atlantic Treaty Organization
NAV	Navigation
NBC	Nuclear, biological, and chemical (warfare)
NNAPS	Night navigation and pilotage system (digital map)
NOE	Nap-of-the-earth
NVPS	Night vision pilotage system
PJH	PLRS/JTIDS hybrid
PLRS	Position location reporting system
PNVS	Pilot night vision system
P^3I	Preplanned product improvement
RA	Radar altimeter
RF	Radio frequency
RWR	Radar warning receiver
SCAT	Scout and attack (LHX missions)
SEAD	Suppression of enemy air defenses (LHX mission)
SINCGARS	Secure VHF communications capability
SSB	Single sideband

GLOSSARY (continued)

STINGER	Air-to-air missile
SWAT	Subjective Workload Assessment Technique
UHF	Ultra-high frequency
V	Vertical
VCASS	Visually Coupled Airborne System Simulator
VCS	Visually coupled system (HMS and HMD)
VIA	Voice interactive avionics
VHF	Very high frequency
VHSIC	Very high speed integrated circuits
VPD	Virtual panoramic display

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Section 1

INTRODUCTION

BACKGROUND

This report documents the methodology and results of an application of the Subjective Workload Assessment Technique (SWAT) to the prediction of workload associated with a next-generation, scout/attack (SCAT) helicopter weapon system (Lightweight Helicopter Family, LHX). Five conceptual single-pilot crew system designs are addressed. Emphasis in both the conceptual designs and in the exploration of workload is on the incorporation of a Virtual Panoramic Display (VPD) as a major component of the man-machine interface.

As part of a joint agreement between the Air Force Aerospace Medical Research Laboratory (AFAMRL) and the U.S. Army Aviation Systems Command (AVSCOM), a technology assessment study titled "Virtual Cockpit for the LHX" was undertaken by the Visual Display Systems Branch, Human Engineering Division, of the AFAMRL. A portion of this document which serves to define the scope of the study reads as follows:

> The central thrust of this study is to investigate and trade-off state-of-the-art control/display technology options, based upon their potential versus technical risks and projected cost for achieving a panoramic virtual image display and control interfaces for use in an advanced helicopter. It is envisioned that such a display interface may be essential for performing the LHX mission using a single crewmember. Of special concern are the feasibility and/or ultimate practicality for generating a wide field-of-view virtual image with control interfaces which optimize the capabilities of the pilot, thereby reducing workload and engendering a sense of "battle awareness."

The present research addresses the workload issue. A subjective measure of workload, SWAT, is applied using highly knowledgeable subjects to attempt to predict the workload that may be expected when the advanced crewstations are applied as the interface between the pilot and weapon system in the conduct of an LHX mission.

OTHER STUDY TASKS

The workload prediction research reported herein formed only one part of the technology assessment study. Two other study areas were treated. The first was an engineering analysis covering the optics, image sources, and electronics technologies needed to provide a VPD. The second was a demonstration of selected aspects of the panoramic display crew system concept, using the AFAMRL Visually Coupled Airborne Systems Simulator (VCASS). The results, conclusions, and recommendations of the overall technology assessment study were provided to the Army in a briefing on 12 July 1984 and to the Advanced Rotorcraft Technology Integration contractor teams on 25 July 1984, both at Wright-Patterson Air Force Base, Ohio.

SUMMARY OF THE REPORT

Section 2 presents an overview of the LHX weapon system concept. Included is AFAMRL's understanding of how the Mission Equipment Package (MEP) provides information sources for the crew system and how the MEP is controlled by the pilot. A composite mission scenario, developed by AFAMRL, is also described. Section 3 contains descriptions of five crew system concepts, each employing a different version of VPD technology. Section 4 discusses workload and its measurement. Particular emphasis is placed on SWAT and its predictive application. Section 5 presents the methodology followed in a field data collection exercise in which SWAT, and other tools, were applied in order to gain early insight into the levels of workload that might be associated with the VPD concepts and LHX mission. Section 6 contains an analysis of the field data, and Section 7 presents the results and conclusions derived from the analyzed data.

Section 2
LHX-SCAT

OVERVIEW

The post-1985 battlefield will be characterized by highly fluid tactical situations which will necessitate the rapid and flexible employment of capable weapon systems in accomplishing a variety of complex mission objectives. Both the fast pace of the land battle and the degree of sophistication of enemy countermeasure systems will force the command, control, communications, and intelligence functions to operate under conditions of incomplete information. This will, in turn, require the employment of tactical assets which are effective in an autonomous role against a variety of targets, which are capable of rapidly responding to changing mission types and objectives, and which are inherently survivable in the face of the numbers, types, and capabilities of enemy threat systems expected to be encountered and overcome. These problems will be compounded by the probability that LHX will operate in a nuclear/biologic/chemical (NBC) environment.

The LHX program goal (as described by Tomaine, 1984) is to provide the scout/attack (SCAT) and utility/observation (UH) aircraft needed to survive in this extremely hostile environment. [The SCAT and UH versions will share common vehicle dynamics (i.e., engine, rotor, drive) but will be based on different fuselages and, more importantly for the purposes of this document, employ different avionic suites, including the crew system.] An enhanced nap-of-the-earth (NOE) flight capability together with increased speed and agility will make it more survivable in combat. Advanced sensors and other avionics will support sustained all-weather, day/night operational effectiveness. The avionics suite will also assure threat warning and countering, including substantial self-protection capability, across the electro-magnetic spectrum. A highly integrated crew system, including large field-of-view (FOV), panoramic information display technology, will support heightened battlefield awareness and reduce crew workload compatible with one-man operability. Ordnance load-out and fire control mechanization will provide substantial offensive and defensive air-to-ground and air-to-air weapon delivery, resulting in greatly increased target servicing rates.

The SCAT mission types include reconnaissance and security, antiarmor/material/personnel, anti-helicopter, suppression of enemy air defenses (SEAD), and cross forward line of troops (FLOT) operations. The last three mission types are new Army 21 missions for light helicopters (lomaine, 1984).

Crewstation design is critical to the achievement of LHX system capabilities. In developing a rationale for LHX crew system concepts, the SCAT mission, because of its higher inherent system tasking and more severe survivability/effectiveness goals, provides an appropriate context for exploring design approaches.

Although the crew size issue (one or two "pilots") is not yet resolved, the LHX has single pilot operability as a design goal. Significant weight savings result, even in the case of a redesign from a two place rotorcraft, which can be capitalized on in terms of increased range and/or increased (weapons) payload.

Around-the-clock operation of the LHX force will be required in order to deny the enemy any possible "night sanctuary." Navigation and pilotage functions must be carried out under all weather conditions, and the weapon system must be capable of acquiring and destroying targets under adverse weather conditions or in the presence of battlefield smoke or obscurants. The force must be capable of deployment to any theatre in the world and must be able to perform sustained operations under adverse environmental conditions. Operations will be carried out from both developed and forward/remote bases, with unconventional landing sites employed as needed.

MISSION EQUIPMENT PACKAGE (MEP)

Two concepts support the consideration of a fully mission-capable, one pilot LHX-SCAT crewstation. These are:

- A High Level of System Automation and Integration
- A Wide FOV Panoramic Virtual Image Display

Together, they provide the enhanced degree of battle awareness needed to rapidly make correct decisions, the superior level of system responsiveness needed to execute these decisions precisely and accurately, and the efficiency of greatly reduced crew workload needed to sustain the high level of system activity associated with the aggressive conduct of the LHX-SCAT mission. It is the successful synthesis of automation, integration, and situational awareness capabilities that makes feasible a single-crewmember approach to the LHX-SCAT mission. Failure in any one of these three man-machine interface (MMI) areas would result in levels of workload beyond the capabilities of single-place operation.

From the pilot's point of view, both literally and figuratively, the virtual panoramic display (VPD) is the focus of the man-machine interface. The LHX crew system is critical to mission effectiveness and survivability. The soldier-machine interface is based on integrated cockpit controls and displays, voice interactive control (of noncritical functions), and advanced fire and flight control systems. Avionics integration [e.g., visually coupled systems (VCS)] and miniaturization [e.g., very high speed integrated circuits (VHSIC)] are required for achieving the required system capabilities within the weight/volume/power constraints of a lightweight helicopter. Many of the mission-required crew system functional capabilities are achieved through the incorporation of an advanced night navigation and pilotage system.

The following subsections identify and describe those portions of the MEP that most directly impact the crew system. Controls, displays, and information sources are addressed.

Controls and Displays

The LHX crewstation will be designed to complement the high degree of automation inherent in the MEP. An enhanced battlefield awareness capability can be supported by the VPD, allowing the pilot-soldier to rapidly and naturally assess both the external world and the status of the rotorcraft's subsystems in order to gather mission-relevant information and to execute combat decisions and tasks. Emphasis is placed on the reduction of workload through automation and information fusion. Backup modes would be provided, although their use would probably result in degraded mission effectiveness and/or increased crew workload.

a. Virtual Panoramic Display (VPD). This display would be the primary source of flight control, pilotage, navigation, and situational awareness information. Imagery and symbology from the several information sources listed below will be presented in combination. (Five alternative approaches to achieving the VPD are described in Section 3.)

b. Multifunction Displays (MFD). Panel-mounted CRTs would be employed (in several optional configurations) to present information (either in conjunction with or as backup to the VPD) and to provide alternative means of controlling subsystems.

c. Integrated Multifunction Keyboard (IMFK). This technology would serve (in several of the options presented in Section 3) as the primary means for selecting and controlling subsystems and weapons. Sensors would be selected, data would be entered into the computer, display formats would be changed, weapons would be selected, etc., by means of this integrated control head.

d. Bezel-Mounted Pushbuttons. These controls would be located around the periphery of the MFDs. The labels which declare the function that button pressing will invoke are presented as alphanumerics or graphics on the MFD surface and would change with both the information currently being presented and with the alternative display formats or system modes that may be requested. The pushbuttons would provide a backup capability to the IMFK.

e. Voice Interactive Avionics (VIA). Selected, nonflight critical cockpit functions would be executed through voice control. Changing radio channels, tuning the attitude/direction finder (ADF) and nav/comm radios, selecting mission equipment modes, changing the transponder code, controlling cockpit lighting, calling up flight computer data, annotating digital maps, and entering/recalling nav waypoint data are all functions that have been suggested for VIA implementation.

f. Collective head and pilot's grip switches. Certain control functions (e.g., slewing a cursor, selecting a weapon) may be executed by means of switches and transducers located on the flight controls. This obviates the need for the pilot to remove his hand from the flight controls.

Information Sources

Both imagery and symbology will be presented to the pilot. The following elements of the MEP serve as information sources for cockpit display.

a. Night Vision Pilotage System (NVPS). A wide field-of-view (120 degrees V by 220 degrees H) night imaging system [employing forward looking infrared (FLIR) or FLIR-like sensing technology] will provide a video rendition of the "real world." NVPS imagery will be aircraft stabilized and displayed on the VPD in registration and at 1:1 scale with respect to the outside world. The imagery will be useful for navigation and terrain/large obstacle (e.g., trees) avoidance.

b. Electro-Optical Target Acquisition and Designation System (EOTADS). This system will be composed of three elements: a narrow field-of-view FLIR sensor, a low light-level television (LLTV) sensor, and a laser designator subsystem. The high resolution, high sensitivity sensors will produce video which is fed to the automatic target recognizer(s) (ATR). The ATR will produce symbology showing target type and location within the NVPS display on the VPD. The pilot may be able to call up the actual video, against which the ATR cue was generated, for display on an MFD or as a video inset in the NVPS imagery. The field of regard of the sensors will be the same as the field of view of the NVPS (i.e., 120 degrees V by 220 degrees H). The laser designator (LD) provides target designation for the HELLFIRE air-to-ground (A/G) missiles (which may be fired in either lock-on before or lock-on after launch modes). LD "armed" and "firing" information will be displayed through symbology. Associated with EOTADS will be an automatic target track capability which will allow sensors, weapons, and/or the LD to track a designated point on sensors, weapons, and/or the LD to track a designated point on the ground (to the limits of their respective fields-of-view/regard). Similarly, automatic sensor/weapon correlation will permit weapons to be assigned against (prioritized) ground tragets. Each of these automated functions will produce corresponding status/mode symbology on the VPD (and/or other display).

c. Millimeter Wave (MMW) Radar. This equipment will exploit a complex waveform to obtain multiple target signature information (cross section, range, range profile, etc.) in both A/A and A/G search modes. The information will be fed to an ATR and target type/position symbology will be displayed on the VPD. Additionally, the MMW radar will be employed to sense, compute, and generate terrain contour traces at four preselected ranges perpendicular to the LHX flight path. These traces will be displayed as overlays on the NVPS video on the VPD.

d. Automatic Target Recognizer(s) (ATR). Target signature data from the FLIR, LLTV, and MMW radar, together with range information from the LD/R, will be exploited to produce target recognition symbols which will be displayed, in their respective locations, against the NVPS video or against digital map imagery on the VPD. (The possible use of ATR-processed video, either on a MFD or as a video inset, has been mentioned.)

e. Automatic Target Handoff System (ATH). The locations of autonomously or externally determined targets is passed to (and from) the LHX targeting system. (Additionally, known target locations may be entered through the keyboard into the targeting system.) Target type/location symbology is displayed on the VPD.

f. **Position Location Reporting System/Joint Tactical Information Distribution System (PLRS/JTIDS) Hybrid (PJH):** This combination of the Position Location Reporting System (PLRS) and the Joint Tactical Information Distribution System (JTIDS) will provide an automated means of obtaining information as to the locations of friendly and enemy forces. (PLRS is a computerized network of ground and airborne radios that automatically reports the position of aircraft, vehicles, and ground troops and provides designated battlefield flight corridors through which network aircraft can navigate and be free from friendly ground fire. JTIDS is a secure, high speed data transmission system between radars, ground troops, air defense systems, vehicles, and aircraft. It provides information on the location of friendly and enemy units.) PJH symbology will be overlayed on the NVPS and/or the digital map.

g. Digital Map: Tactical map information will be stored on the LHX in digital form. Driven by present position information from the navigation processor, the map will display natural and cultural features in the vicinity of the aircraft. Forward perspective terrain elevation map information would be presented, in registration and at 1:1 scale with respect to the outside world, on the VPD. Plan view map information would be presented on an MFD employing full color rendition. The map data base and processor would support the computation and display of intervisibility information (i.e., clear line-of-sight) and, exploiting threat type and location data (such as from the PJH), would be capable of generating contour lines of constant LHX survivability for route selection. Other information, overlayed on the digital map display, would include waypoints, ground speed, time-to-waypoint/target, distance to waypoint/target, range (map scale), and navigation course.

h. Radar Altimeter (RA): This subsystem will provide accurate altitude information to the point on the ground directly beneath the rotorcraft. This information will be displayed to the pilot as a digital readout (or graphic) on the VPD.

i. Airborne Survivability Equipment (ASE): Composed of a RF warning receiver (RWR) and display system, a RF jammer, an IR jammer, and a laser warning receiver, this suite will detect, identify, and respond to threat systems. The direction-finding capability of the equipment will provide approximate threat location information. Display of these data in the crewstation will support threat countering and route (re)planning.

j. CO^2 Laser: This technology represents a possible growth option for the LHX. It would be used for obstacle (particularly wire) detection. Laser "armed" and "firing" status information would be displayed on the VPD. Obstacle location information would also be displayed to the crewmember.

k. Weapon Delivery: Weapon symbology for gun, missile, and laser status will be displayed on the VPD.

l. Backup Instruments: Although the VPD will be the primary flight control display, dedicated "round dial" instruments will be maintained as backup to the primary display. These will include airspeed, barometric altitude, vertical speed, attitude (ADI), and clock.

MISSION SCENARIO

Two objectives were addressed in the process of creating a representative mission scenario for the LHX/SCAT weapon system. First, the scenario served to provide context in seeking to understand how elements of the MEP, including the VPD, might contribute to the total mission capability of the aircraft. (It also served as a means of verifying that all required system functions could, at least at the present conceptual level, be supported by capabilities inherent in the MEP.) Second, the scenario provided the situational context required during the administration of the Pro-SWAT instruments for workload estimation.

The mission was created on the basis of available information including mission profile data prepared by the Directorate of Combat Developments. It was refined through discussions with representatives of the Army Aviation Center and the LHX Program Management Office.

Description

A composite mission was created in order to assure that a wide variety of crewstation functions would be represented. Thus, the mission includes segments which individually emphasize antiarmor, SEAD, and antiair tasking. Changes in mission priorities occurred as the mission progressed from segment to segment, which caused additional activity in the cockpit.

The mission is set in central Europe, shortly after the outbreak of conventional warfare. Army ground forces (tanks and infantry), supported by AH-64 APACHE advanced attack helicopters (AAHs), are holding a major enemy thrust along lines of communication (LOCs) to the north of the LHX penetration route. An eight-ship flight of LHX/SCATs is tasked with attacking a Soviet armored battalion located at an assembly area 30 to 40 km beyond the forward line of troops (FLOT). Destruction of this second echelon force will prevent reinforcement of the already engaged enemy units.

Figure 1 presents a graphic overview of the LHX/SCAT mission. The eight-ship flight (call sign BLACKJACK) takes off from the base (Point A) at 2300 hours local time. All aircraft are identical and each is armed with four HELLFIRE A/G missiles, two STINGER A/A missiles, and 260 rounds of 30 mm ammunition for the gun. The primary targets are the 37-plus enemy tanks that constitute the mass of the armored battalion. Secondary targets are the mobile air defense weapons (ZSU-XX and SA-XX) colocated with the tanks. Tertiary targets are the armored personnel carriers (APCs), trucks, and other support vehicles that comprise the remainder of the enemy force. Time on target is briefed to be 0010 hours local. The mission duration is to be two and a half hours, including the attack against the enemy ground force and return to base. The weather both along the route and in the target area is 34°F, patchy fog, and cloud ceilings at 4,000 feet. High cover will be provided by a four-ship flight of Air Force F-15s at

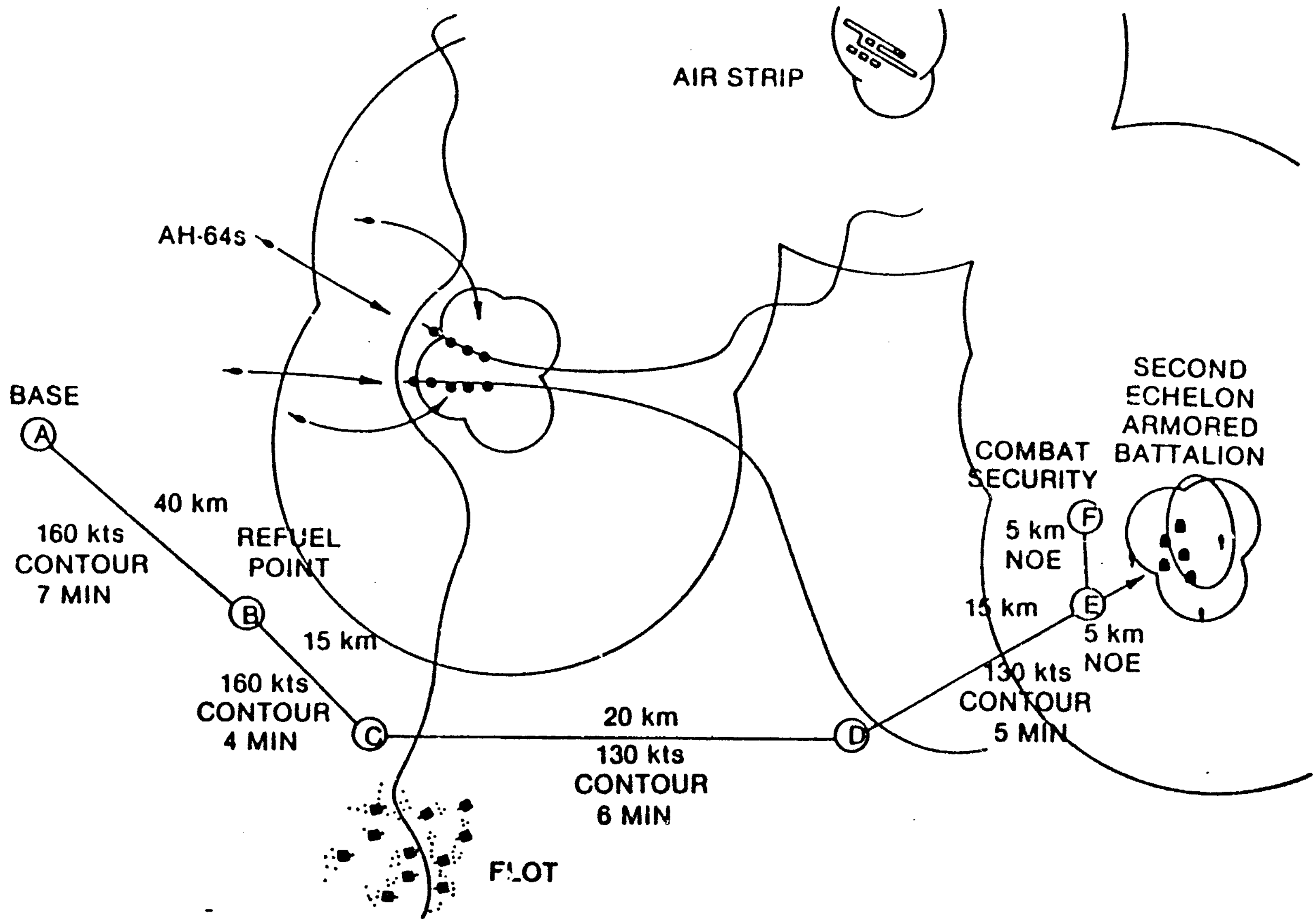

Figure 1. Overview of LHX/SCAT Mission

15,000 feet which will be operating in the area under airborne warning and control system (AWACS) direction. The LHX tactics for the mission are briefed to emphasize contour flight between the FLOT and the planned battle position during both ingress and egress; terrain and foliage masking, together with high speed dashes across open areas, provide for stealthy transit of enemy-held terrain and offer the advantage of surprise in any chance encounter with enemy defenses.

The LHXs will be vulnerable to numerous enemy weapon systems during the course of the mission. These threat systems will be defeated by avoidance, evasion, countering, or engagement. Threat systems for which a high probability of encounter exists include air defense artillery (guns, directed energy weapons, and surface-to-air missiles), surface-to-surface artillery, tank main guns, soldier-fired and crew-served small caliber guns, ground launched antitank guided missiles, and enemy close air support (CAS) aircraft (including both high performance, fixed wing types and helicopters). (The circular arcs depicted on Figure 1 represent the threat envelopes of the enemy surface-to-air systems.)

Although constituted of identical rotorcraft, carrying identical weapon loads, three distinct roles are established in terms of mission tasking. Two aircraft, one of which serves as the mission commander, are assigned primary responsibility for combat security. Two others are tasked to serve the flight as scouts during penetration, ingress, and egress and to perform SEAD during the attack phase of the mission. The remaining four ships are tasked to carry out the antiarmor attack. Each aircraft is capable of performing all required functions; the differentiation in the roles to be performed during the execution of the mission simply reflects a prioritization in tasking.

After takeoff, the cell performs contour flight (160 kts, 40 km) to a refueling point (B) where tanks are filled. The cell transits (contour flight, 160 kts, 15 km) to point C where final subsystem checks are carried out, the penetration formation is established, and monitoring for enemy threat systems begins. The FLOT is crossed and ingress (between points C and D) is conducted so as to maximize stealth and surprise (contour flight, 130 kts, 20 km). When point D is achieved, the flight turns toward the planned battle position (point E) and employs contour flight to reach it (130 kts, 15 km). (Disengagement from battle, egress, and return to base are performed in similar fashion.)

Tasks

The following sequence of tasks (Table 1), described from the viewpoint of the mission commander, reflects the activities of the flight from the time that it approaches the battle position (point E) to the time that it departs it. Although sequentially numbered, many tasks may in fact be grouped for simultaneous execution. Information sources exploited in performing major tasks are identified.

TABLE 1. LHX/SCAT MISSION SCENARIO TASKS

1. Fly aircraft at minimum contour altitude (using primary flight instruments on VPD, MMW terrain traces, and NVPS)
2. Monitor for threats (VPD and/or RWR)
3. Command system self-tests to assure own-ship health
4. Check fuel status
5. Select/verify appropriate map display (scale and orientation)
6. Correct aircraft/flight heading to point E and note ETA/ETE (VPD)
7. Crosscheck primary and backup flight instruments
8. Configure displays for air-to-ground attack
9. Notify flight:
    a. at point E
    b. to descend and slow to hover
    c. that the combat security aircraft are cleared to fly north to point F (NOE, 5 km)
10. Fly aircraft to NOE and take up hover (VPD)
11. Check that all aircraft are in hover and are masked (visual, NVPS, and/or EOTADS)
12. Notify attack force to hold position
13. Notify second scout to move forward in NOE
14. Fly ownship, NOE, to first observation position
15. Hover, masked, at observation position
16. Acknowledge combat security ships are on station
17. Confirm second scout in position and is ready to begin target area search
18. Command "unmask"
19. Fly aircraft to HOGE, unmasked (NVPS)
20. Scan target area (visual, NVPS, EOTADS, MMW, ATR)
21. Call general target locations to second scout (comm)

TABLE 1. LHX/SCAT MISSION SCENARIO TASKS (continued)

22. Send targets to scout and attackers (ATH, PJH)
23. Observe/monitor contact by SAM (ASE, RWR, VPD) and send to second scout
24. Confirm ECM on (ASE, VPD)
25. Command second scout to remask and confirm his safety
26. Take up hover in position masked from mobile SAM
27. Acknowledge SAM calls from scout
28. Scan for other threats and targets (ASE, EOTADS)
29. Select optimum approach route for attack force
30. Handoff threat/target location to attackers and confirm receipt (ATH, PJH, comm)
31. Transmit attack route and tactic
32. Command scout to move to new position
33. Fly, NOE, to new position (VPD, NVPS, MMW)
34. Hover, masked
35. Monitor PLRS for scout location and attack force movement (VPD)
36. Acknowledge attack force in position
37. Send updated location of SAM
38. Review tasking with flight (scouts to perform SEAD and four ships in antiarmor role)
39. Command "unmask" for all aircraft
40. Fly toward SAM, NOE (VPD, RWR)
41. Monitor for threats (RWR, ASE)
42. Acknowledge SAM contact by scout
43. Acknowledge SAM contacts by attackers
44. Call SAM contacts and send locations
45. Command scout to hold position

TABLE 1. LHX/SCAT MISSION SCENARIO TASKS (continued)

46. Fly, NOE, to effective weapon range (VPD)
47. Select HELLFIRE
48. Select SAM target (VPD, ATR, EOTADS)
49. Command LD autotrack
50. Slow aircraft to HOGE
51. Confirm HELLFIRE lock-on (VPD)
52. Fire HELLFIRE
53. Acknowledge AAA fire from attackers
54. Call "SAM destroyed"
55. Notify force to take advantage of reduced SAM coverage
56. Observe/send tank movements (VPD, EOTADS, ATR, ATH, PJH)
57. Fly, NOE, towards tanks
58. Fly maximum performance maneuver to avoid AAA fire
59. Fly, NOE, toward new masking position
60. Receive and acknowledge "Bandit" warning call from AWACS
61. Confirm combat security ships have received Bandit call
62. Acknowledge F-15s have "negative targets"
63. Hover, masked, in new position
64. Monitor PJH for hostile aircraft
65. Call AWACS for Bandit location
66. Monitor PJH (VPD)
67. Acknowledge combat security force has four HIND, 200 feet, engaging
68. Select ambush position between hostiles and A/G attack (VPD, map)
69. Command second scout to ambush position
70. Fly, NOE, toward ambush location (VPD, NVPS, MMW)

TABLE 1. LHX/SCAT MISSION SCENARIO TASKS (continued)

71. Acknowledge combat security call: two HINDs shot down, two penetrating security, using IR flares
72. Select A/A mode on displays (VPD)
73. Select STRINGER
74. Scan for HINDs (VPD, NVPS, EOTADS, MMW)
75. Monitor PJH (VPD)
76. Acknowledge loss of A/G LHX to ground fire
77. Obtain (VPD, ATR, MMW, EOTADS) and call HIND sighting to second scout
78. Slow aircraft to HOGE
79. Select target
80. Confirm STINGER lock-on (VPD)
81. Call "engaging"
82. Confirm target within range (VPD)
83. Fire STINGER
84. Fly aircraft to avoid gunfire from second HIND
85. Acknowledge "engaging" call from second scout
86. Monitor PJH for other aircraft (VPD)
87. Acknowledge destruction of second HIND
88. Fly, NOE, toward antiarmor LHXs
89. Check fuel status
90. Call flight for fuel/weapon status
91. Command all aircraft to disengage and return to battle position (Point E)
92. Select map display and find heading to B.P.
93. Select air-to-ground mode
94. Fly, NOE, on course toward B.P.

TABLE 1. LHX/SCAT MISSION SCENARIO TASKS (continued)

95. Monitor PJH for other aircraft
96. Notify flight to hover at B.P. until flight reformed
97. Monitor for aircraft approaching B.P. (VPD, PLRS, NVPS)
98. Hover, masked, at B.P. until all friendly aircraft have rejoined
99. Call "flight departing B.P."

Section 3
CREW SYSTEM CONCEPTS

REQUIREMENTS FOR A VPD

One of the major factors that serves to structure the LHX crew system concepts is the specification that the weapon system is to be single-pilot operable. A one-place aircraft, exploiting a highly capable MEP and performing a complex mission, must be highly integrated and highly automated in order to carry out its assigned mission. The VPD serves as the major integrative force in the crew system.

MEP Drivers for a VPD

To the extent that the single crewmember may be considered a part of the MEP, a single, primary display is required to support his accomplishment of situational assessment, decision-making, and functional execution tasks. An integrated flight control display is required to reduce workload and to support "heads-up" flying (a concept already supported by the presence of VIA and the presence of switches/transducers on the flight controls). The VPD is the primary flight control instrument. The NVPS provides the pilot's primary source of contact with the external world (especially at night) and the VPD is the means of displaying that imagery. The digital map (forward perspective mode) provides a data base of terrain elevation information and of cultural and natural features. The VPD serves to transfer that information to the pilot. Correlation of NVPS and digital map information provides an autonomous navigation update capability. The NVPS and/or digital map provide contextual meaning to the terrain traces generated by the MMW radar and to the target location cues provided by the ATR and ATH. The VPD serves to fuse sensor imagery, computer generated imagery, and radar and target type/priority symbology.

Mission Drivers for a VPD

The nature of the LHX-SCAT mission also makes a compelling argument for the inclusion of a VPD as a situational awareness display. With a single pilot, all sources of mission-critical information must be presented for immediate assimilation. Division of duties is not possible. The penetration, ingress, attack, and egress phases of the mission are typified by maneuvering at low altitude (at and below tree-top level). Stealth helps to assure survivability. Target acquisition and weapon delivery will be performed with minimum exposure of the LHX to threats. Threat detection, assessment, and countering will be performed rapidly and accurately. Multiship formations and tactics will be maintained. The overall battle management function will be typified by numerous, rapid decision-making/execution events. The VPD will support these attributes of a mission-effective weapon system.

VPD CONCEPTS

In order to explore the VPD, particularly with respect to crew workload, a set of crew system concepts were developed to a first order level of detail. In structuring these concepts, certain assumptions were made. It was assumed to be highly desirable to have the FOV of the NVPS available as the FOR of the VPD. Thus, the crew system concepts are based on VPDs which exhibit increasing FOVs. The availability of digital map information that is suitable for display in full color (similar to a paper chart) suggested that color displays were appropriate. Thus, color display capabilities are included in the concepts. Hands-on flight control was assumed to be desired. Thus, the concepts exhibit decreasing reliance on the MFPK (which requires manual operation). Additionally, where a specific VPD concept supported it, evolutionary adjustments were made to the remaining controls and displays.

A baseline crew system and four variations (options) derived from it are presented below. The capabilities of the VPD used in each configuration variant served as the departure point for configuring the total crew system. To the extent that the increased FOV of the VPD options can be considered to be an enhancement to system capability, the five concepts represent a baseline configuration and four enhanced versions of it. The baseline LHX configuration could fly now. It is very similar to the AHIP-equipped KIOWA. Option 1 is similar to the AH-64 APACHE and employs a monocular HMD as the

VPD. Option 2 employs a medium FOV, binocular helmet-mounted display while Option 3 employs a wide FOV, binocular HMD. Option 4 exhibits a wide FOV, cockpit-mounted display as the VPD.

Baseline

Figure 2 illustrates the baseline crewstation concept. Key elements of the concept include the VPD, the MFDs, and the control mechanization.

a. VPD: A 20-degree V by 30-degree H HUD serves as the primary flight control and imagery/symbology display. Flight control symbology and alphanumerics (pitch ladder, velocity vector, radar altitude, etc.) and weapon delivery symbology are presented. NVPS sensor imagery and forward perspective view digital map imagery are presented on the VPD in registration and at 1:1 magnification with respect to the outside world. Target location symbology and radar terrain traces are overlayed on the imagery. A "snap-look" or "look-into-turn" feature allows the pilot to command the NVPS imagery to slew 1/2 of the HUD FOV left, right, up, or down, allowing exploitation of a 40 degrees V by 60 degrees H FOR without requiring a change in the aircraft's flight path.

b. MFDs: Two, color MFDs (one 5 inches by 5 inches and the second 7 inches by 7 inches) are mounted in the central panel. They will be used to display the plan view digital map, to verify navigation data, and to provide a "head down" source of flight control and navigation information such as Electronic Horizontal Situation Indicator (EHSI) and Electronic Attitude Direction Indicator (EADI) displays.

c. Controls: The pilot grip and collective head are the flight controls. The MFPK serves as the primary means of controlling MEP subsystems and changing modes or display formats. Pushbuttons, located around each MFD, will also serve as a second means in controlling the MEP. VIA is employed to control noncritical system functions.

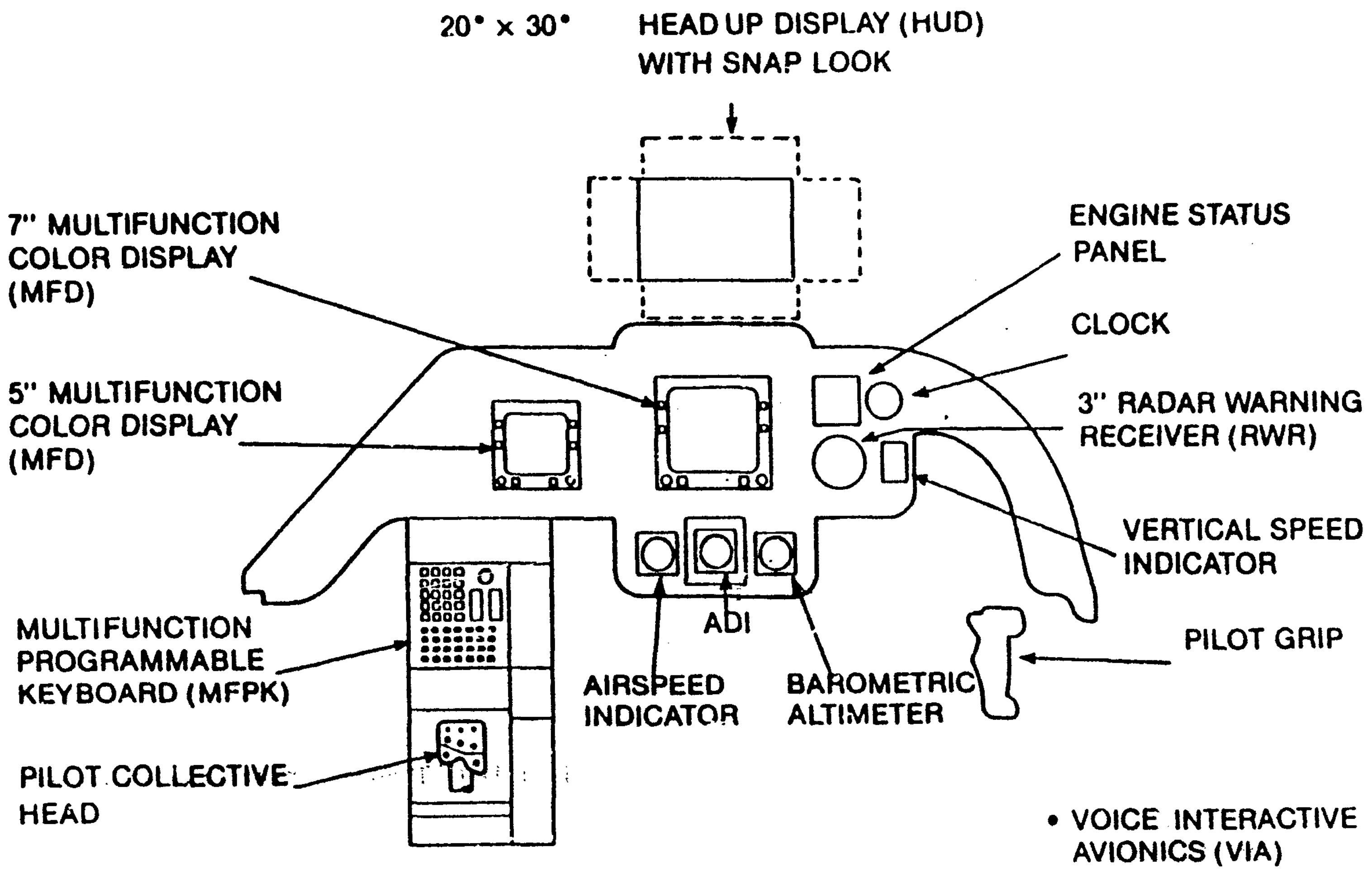

Figure 2. LHX Baseline Configuration

d. Other: Dedicated, conventional "round dial" type displays are provided for backup instrumentation. These displays are arranged around the front panel and include engine status, clock, radar warning information, vertical speed indicator, airspeed indicator, ADI, and barometric altitude.

Option 1

a. VPD: This configuration is depicted in Figure 3. Option 1 differs from the baseline in that the HUD has been replaced by a monocular, helmet-mounted display (HMD). The FOV of the HMD is 30 degrees V by 40 degrees H. The FOR of the HMD is (at least) the 120-degree V by 220-degree H FOV of the NVPS.

b. Other: The HMD employs six degree-of-freedom head position sensing to determine the boresight of the pilot's look angle. (This direction of look is used in determining the portion of the NVPS video, and other registered information, to display to him at any instant in time.) Given head position sensing, then the HMD could logically also carry with it a helmet-mount sight (HMS) capability. The HMS in Option 1 is an aiming reticle centered in the HMD FOV. It is employed for designating waypoints to the navigation computer and targets to the weapon delivery computer or to the ATH. VIA is implemented as in the baseline configuration.

Option 2

a. VPD: A binocular HMD is employed. Its FOV is 60 degrees V by 90 degrees H, with 30 degrees H overlap, and its FOR is the 120-degree V by 220-degree H FOV of the NVPS. Figure 4 depicts this configuration.

b. MFD: The two color MFDs of the baseline and Option 1 are replaced by a single 12-inch V by 22-inch H, color, panel-mounted display. All information previously available (in the baseline and Option 1) is still available on this single, large panel-mounted

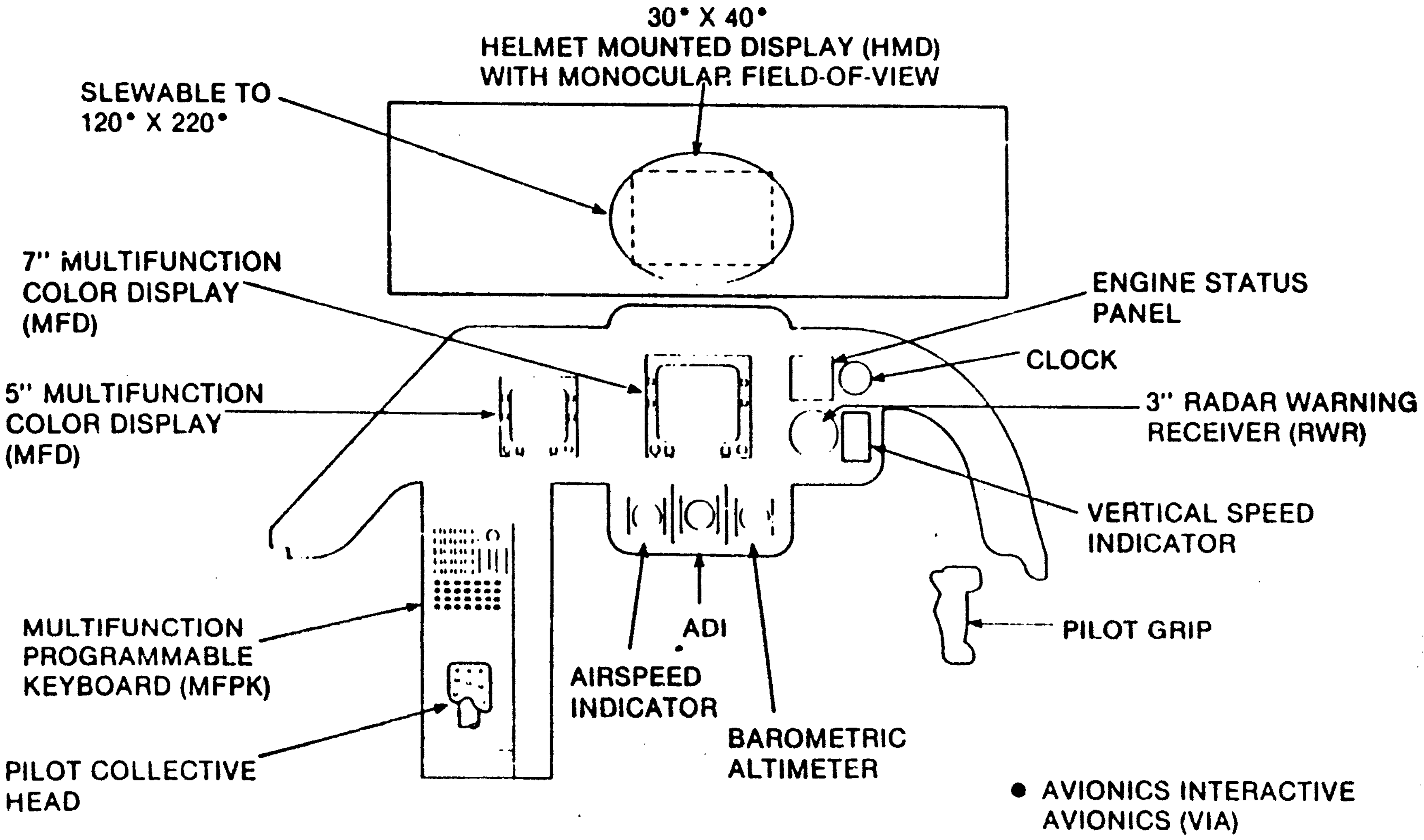

Figure 3. LHX Option 1 Configuration

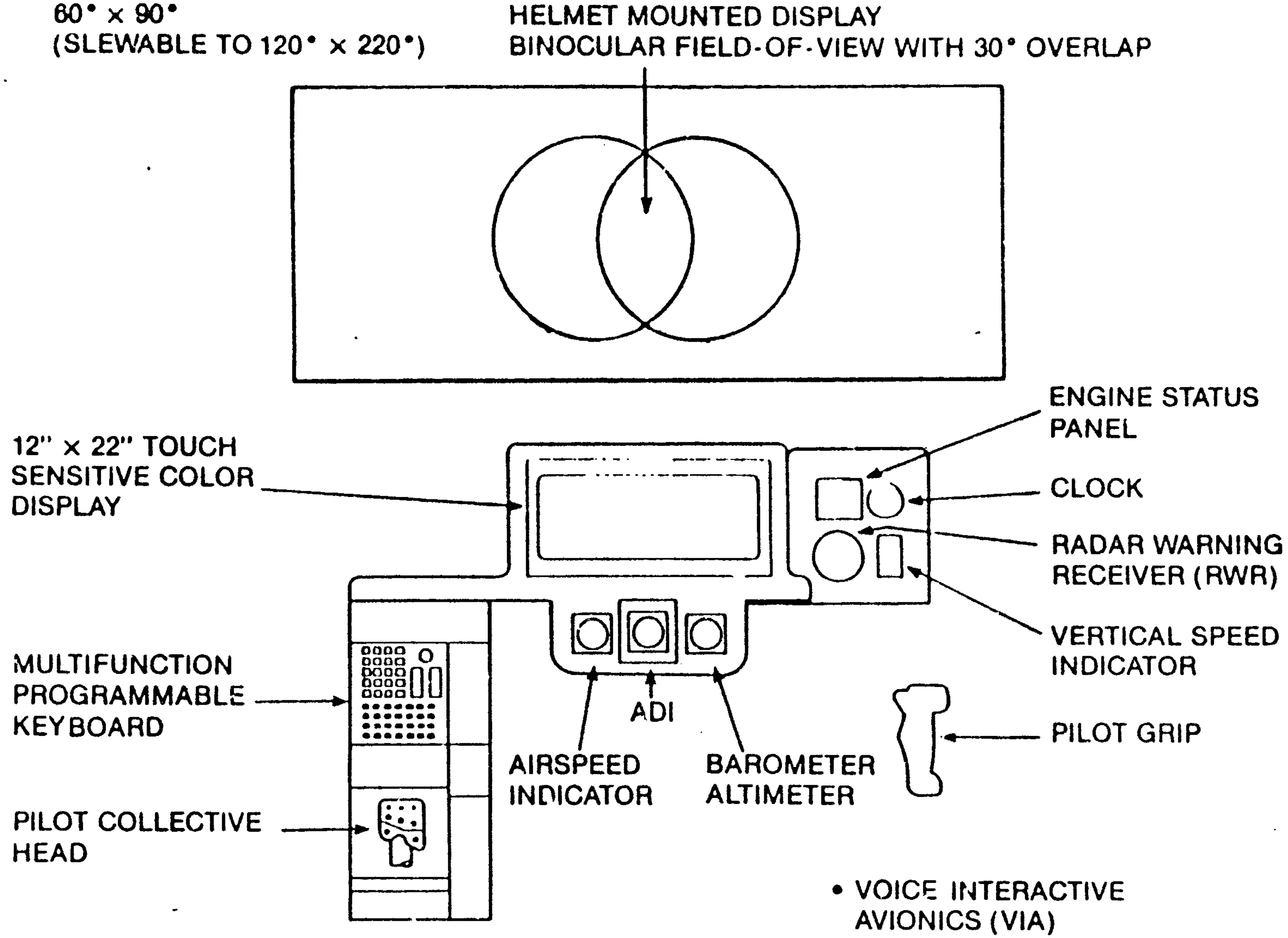

Figure 4. LHX Option 2 Configuration

Because of its size, multiple information sources can be presented simultaneously.

c. Controls: The MFD is equipped for touch control. That is, the pilot's finger need only point to an area of the display surface in order to activate some function. By presenting a menu of functions on the display surface and exploiting touch control, display formats can be changed and/or MEP subsystems can be controlled. This capability is assumed to make the MPD at least co-equal to the MFPK as the primary subsystem controller. VIA is retained for noncritical functions.

Option 3

a. VPD: The medium FOV binocular HMD (of Option 2) is replaced with a large FOV (60 degrees V by 120 degrees H) binocular HMD in this configuration. (See Figure 5.) The FOR remains the same. The 40-degree overlap is considered to be sufficiently great to adequately support the coding of information for stereoscopic perception. This additional coding dimension could be employed to emphasize the priority, spatial or temporal proximity, or criticality of the information along an apparent distance axis.

b. MFD: Because of the larger FOV of the VPD, the size of the MFD is reduced to a 7-inch by 7-inch color display. Touch control is retained. MFD display formats are now generated within noncritical regions of the FOR of the HMD, and a "virtual" MFPK is created.

c. Controls: The HMS capability is exploited both as a target designator and as a controller in conjunction with the virtual MFPK. (The actual, hardware-based MFPK is retained as a backup control head.)

d. Other: The previously dedicated "round dial" displays are removed. They may be called up as virtual display information

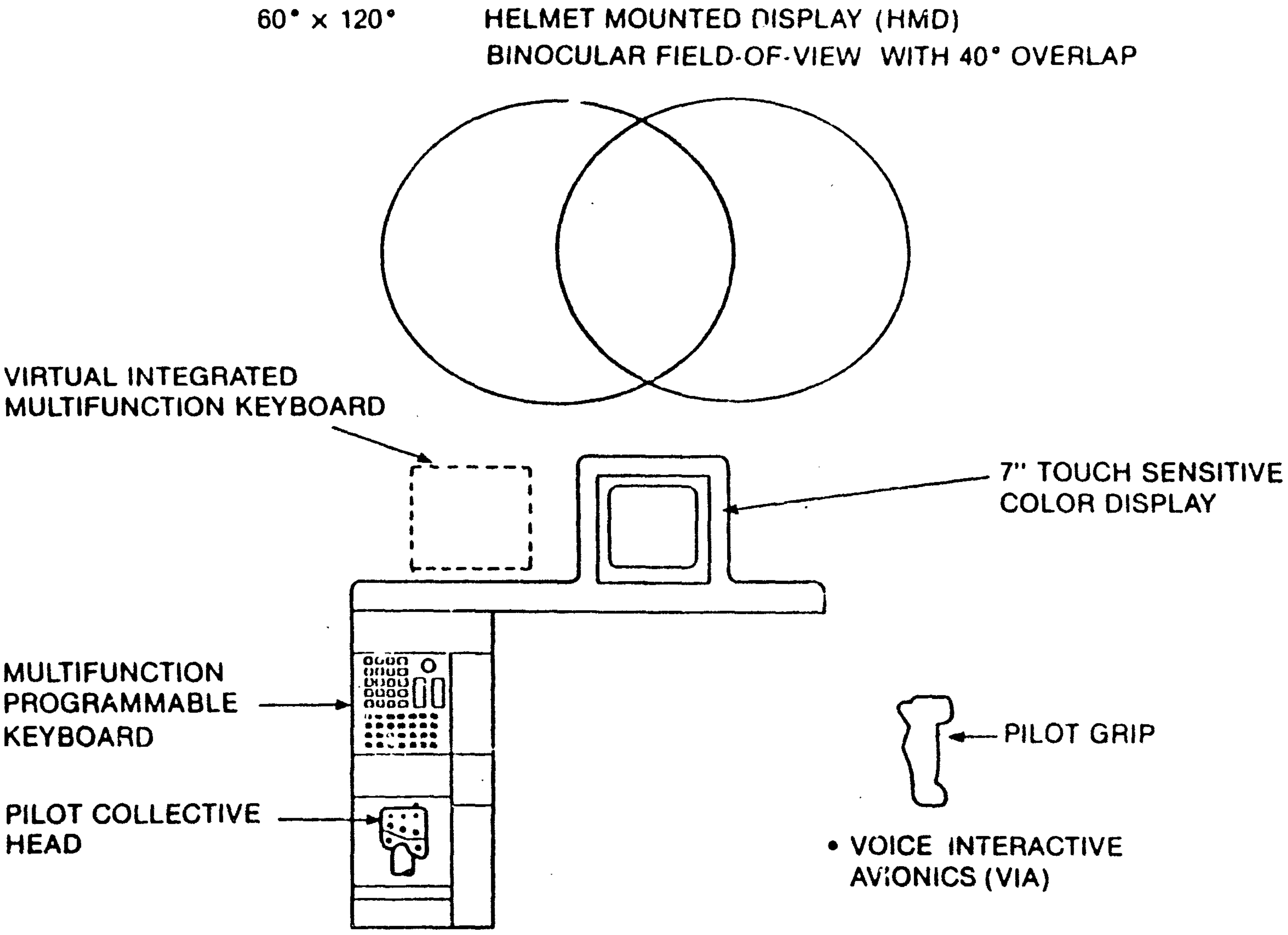

Figure 5. LHX Option 3 Configuration

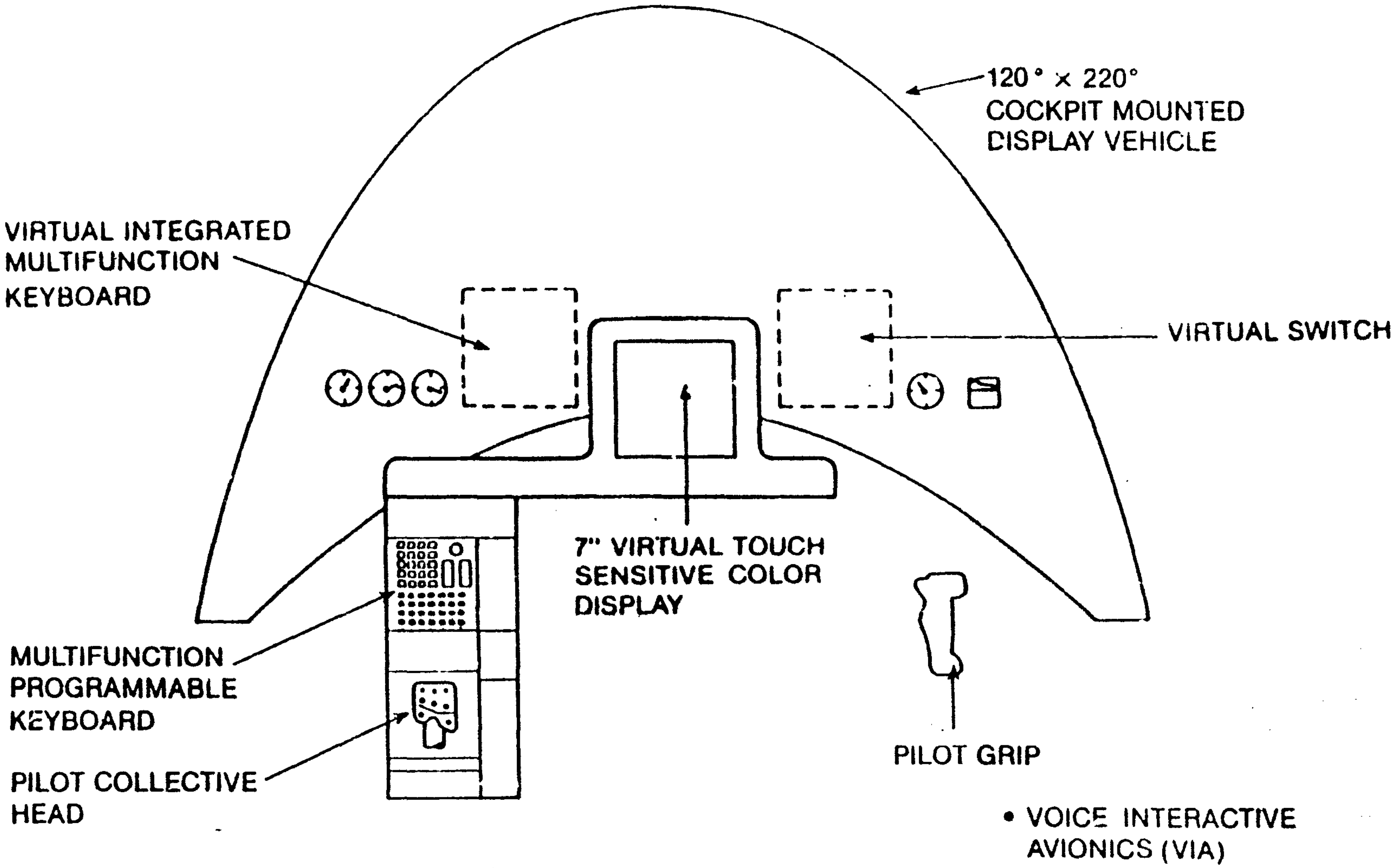

Figure 6. LHX Option 4 Configuration

TABLE 2. OVERVIEW OF LHX CONFIGURATIONS

DISPLAY	CONTROLS	SPECIAL FEATURES	BACK-UP INSTRUMENTATION
BASELINE • 20° x 30° HEAD UP DISPLAY (HUD) • 5" x 5" COLOR MULTI-FUNCTION DISPLAY (MFD) • 7" x 7" COLOR MFD • 3' RADAR WARING RECEIVER (RWR)	• MULTIFUNCTION PROGRAMMABLE KEY-BOARD (MFKB) • VOICE INTERACTIVE AVIONICS (VIA)	• SNAP LOOK - ± ½ HUD FIELD-OF-VIEW (FOV) - LEFT, RIGHT, UP, DOWN	• AIRSPEED INDICATOR • BAROMETRIC ALTITUDE • ALTITUDE DIRECTION INDICATOR • VERTICAL SPEED INDICATOR • CLOCK • ENGINE STATUS PANEL
OPTION #1 • 30° x 40° HELMET MOUNTED DISPLAY (HMD) - MONOCULAR • 5" x 5" COLOR MFD • 7" x 7" COLOR MFD • 3" RWR	• SAME AS BASELINE	• HELMET MOUNTED SIGHT (HMS) - TARGET DESIGNATOR ONLY	• SAME AS BASELINE

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TABLE 2. OVERVIEW OF LHX CONFIGURATIONS (continued)

DISPLAY	CONTROLS	SPECIAL FEATURES	BACK-UP INSTRUMENTATION
OPTION #2			
• 60° x 90° HMD · SLEWABLE TO 120° VERTICAL 220° HORIZONTAL · 30° FOV OVERLAP • 12" x 22" COLOR DISPLAY	• 12" x 22" COLOR DISPLAY TOUCH SENSITIVE • MFPK • VIA	• SAME AS OPTION #1	•SAME AS BASELINE
OPTION #3			
• 60° x 120° HMD • 40° FOV OVERLAP	• VIRTUAL INTEGRATED MULTIFUNCTION KEY-BOARD (IMFKB) • VIA	• STEREO HMD • HMS (TARGET DESIGNATION AND SWITCHING)	• MFPK • 7" x 7" COLOR MFD TOUCH SENSITIVE
OPTION #4			
• 120° x 220° COCKPIT MOUNTED DISPLAY VEHICLE	• VIRTUAL SWITCHING HEAD CONTROL • VIRTUAL IMFKB • VIA	• LINE OF SIGHT SENSING	

workload are exhausting and stressful and do utilize the body's physical energies. The proportion of physical to mental energy load that is required by a given task is difficult to quantify; "all tasks have some of each component in their total contribution to the human operator workload" (Johannsen et al., 1979). The predominance of mental tasks is responsible for unprecedented increases in the amount of workload experienced by the operator which may compromise the performance of the entire human/machine system (Reid et al., 1984).

Operationally, workload has been defined objectively and subjectively. Moray (1980) made a distinction between imposed mental load and subjective mental load. He defined imposed mental load as the load demanded by the task and measured by task parameters. Subjective mental load he defined as the load perceived or experienced by the operator.

Just as there is no single agreed upon definition of workload, there is no universally accepted metric of workload. Considerable scientific effort has been directed toward defining workload and developing methods for measuring it (Reid et al., 1984). However, most researchers do agree upon a set of characteristics that any measurement technique should possess. Any measurement technique should have face validity; it should seem an intuitively appropriate measure. It should be sensitive to the entire range of specific human performance from underload, where almost none of the operator's capacity is being employed, to overload, where all of the operator's capacity is being utilized and more is needed. The measure should be nonintrusive or at least reasonably unintrusive; measures which interfere with the operator's normal activities may yield invalid results. Generalizability is an important attribute; the measure should yield stable reliable results between and within people and situations.

There are three major categories of workload measurement techniques: physiological, behavioral or performance, and subjective. Physiological methods involve the measurement of one or more variables related to the human physiological process. The underlying assumption is that as operator workload changes, involuntary changes take place in the physiological processes of the human body (body chemistry, nervous system activity, circulatory or respiratory activity, etc.) (Wierwille, 1979). O'Donnell (1979) gives a complete discussion of the various physiological measurement techniques.

The logic underlying behavior/performance-based measures is that external behavior reflects internal events and processes. It seems logical to suppose that an operator is beginning to exceed his ability to process information and/or generate appropriate responses when he begins to make errors. The two major classes of performance-based measures are primary or single task measures and secondary or dual task measures. In the former, performance is measured for one or more tasks performed separately; in the latter, two tasks are performed simultaneously and performance on the lower priority task is taken as an index of the amount of mental capacity not required for the primary task. Both methods are based on the assumption that there is an upper limit to the amount of effort that can be exerted to meet task demands, and that decrements in performance will begin to appear as this upper limit is approached. Single task measures are discussed in detail by Shingledecker, Crabtree, and Acton (1982) and secondary task measures by Eggemeier (1981).

The use of subjective measures of workload is based on the rationale that if an operator feels loaded and effortful, he is loaded and effortful, regardless of what performance measures might demonstrate (Johannsen et al., 1979). Johannsen et al. have suggested that prior to performance breakdown, the operator might be working harder to avoid such decrements, and that subjective feelings could be used as an indicant of the additional effort which precedes degraded performance. Gartner and Murphy (1976) have indicated that when subjective impressions of workload are accepted, the operator's direct perception or estimati . of his feelings, exertion, or condition may provide the most sensitive and reliable indicators of workload. Moray (1980) has pointed out that an objectively easy task may be experienced as difficult due to factors such as fatigue or motivation. Given appropriate instructions and a balance between speed and accuracy, an objectively difficult task may be experienced as less effortful or difficult. In addition to their theoretical importance, subjective techniques have a number of characteristics which contribute to their potential utility as measures of operator workload (Eggemeier, 1981). They are relatively easy to implement and support when compared with many physiological and performance-based measures. Subjective measures minimize instrumentation requirements and, therefore, might be more easily implemented in an operational environment. If implemented correctly, the measures can be relatively nonintrusive and should not disturb primary task performance. If the general factors that contribute to workload can be identified, subjective measures could be applicable across a wide range of situations, while performance-based techniques are, by necessity, situation specific.

A variety of subjective assessment techniques have been reported in the literature. Daryanian (1980) used a Thurstonian paired-comparison procedure to generate an interval scale of workload related to a multicomponent decision task. Hicks and Wierwille (1979) applied the method of equal appearing intervals to generate rating scale responses. This method successfully discriminated a number of workload conditions in a driving simulator. Borg (1978) has reviewed a program which made use of magnitude estimation techniques and category scales to develop indices of perceived difficulty in a group of physical and cognitive tasks. The program explored the relationship between perceived difficulty and task characteristics for several cognitive tasks. High correlations were obtained between subjective and objective measures of difficulty, supporting the capability of subjective ratings to reflect objective levels of task difficulty.

SWAT

Most subjective assessment techniques have been developed for a particular application and are not easily generalizable. SWAT has been developed by the AFAMRL as a candidate generalized procedure for scaling pilot mental workload (Reid et al., 1981). SWAT uses a psychometric technique known as conjoint measurement to construct interval level workload scales from ordinal rankings of combinations of levels on three contributory dimensions.

Conjoint measurement (Coombs, Dawes, and Tversky, 1970; Krantz and Tversky, 1971) is a technique by which the joint effects of several factors are investigated and the rule or composition principle that relates the factors to one another is extracted from the data. A major advantage of this procedure is that only the ordinal aspects of the data are required for the production of an interval level scale which represents the joint effect of the factors.

SWAT distinguishes three levels for each of three dimensions: time load, mental effort load, and psychological stress load. These are adaptations of the categories defined by Sheridan and Simpson (1979). Time load refers to how much time is available for an operator to perform a task; this includes both overall time and task pacing. Mental effort load refers to the amount of attentional capacity or effort required without regard to the amount of time available or task pacing. Stress load refers to anything that makes the task more difficult by producing anxiety, frustration, and confusion; this includes such things as fatigue, stress, and fear, as well as physical stressors like vibration, g-loading, and heat. The primary assumption of SWAT is that workload can be adequately represented by the combination of these three dimensions.

SWAT is a two step process consisting of a scale development phase and an event scoring phase. These are two distinct events which occur at different times. During the scale development phase, the data necessary to develop a workload scale are obtained from a group of subjects. At the event scoring phase, the subjects rate the workload associated with a particular task and/or mission segment.

The three dimensions (time, effort, stress) taken in all possible combinations yield a 27-cell three-dimensional matrix to represent workload. To develop the scale, the subjects rank order the 27 combinations of descriptors according to the workload represented by each combination. The results of the ranking procedure are then used to develop an overall interval workload scale which represents the joint effect of the three dimensions. The composition rule for the ordered data is defined through a series of axiom tests; possible combinatory rules include additive, distributive, and joint distributive (Krantz and Tversky, 1971). When the appropriate rule has been identified, the scaling transformation is computed.

The event scoring phase is an implementation of the scale as a dependent variable. This is accomplished, as with other rating procedures, by analyzing the tasks or mission scenario to determine what ratings are needed, what ratings are possible given the scenario, and when the ratings should be obtained. A major positive attribute of SWAT is the simplicity of the event scoring procedure. The events are rated using the same descriptors previously used for scale development. Asked to provide a SWAT rating for a particular event, a pilot would assign either a 1, 2, or 3 to each of the three dimensions of time load, effort load, and stress load experienced during that event. The numbers for each level of the three dimensions are defined as in the scale development phase, and these definitions are supplied to the pilot for reference. These three ratings correspond to one of the combinations created in the ordering procedure for scale development. The scale value computed for this particular combination of the three factors is the subjective workload score assigned to the event.

Although all three classes of workload measures have been successfully employed in the system development process, these techniques have been designed almost exclusively for application to laboratory research, flight test, or simulation studies. These workload measurement techniques are applicable for evaluating the workload associated with an existing system or when initial equipment configurations are available during the middle and late stages of system design. Workload metrics can make significant contributions to the design process during these phases. However, a number of critical decisions affecting the human operator are made at the predesign phase where design options are on paper only. Analytic tools such as task analysis, time line analysis, and various systems models are currently being used by systems designers to address operator factors in these early phases of the development process. These analytic methods are useful in defining the human-machine interface but address operator workload in an indirect or informal manner. Although it is customary to acquire information from the user during system development, informal and unstructured approaches may encourage the user to provide information in areas beyond his expertise. If operator workload is to be adequately considered in the predesign phase, a method is needed to provide quantitative predictors of operator workload which can be used along with cost and effectiveness to permit optimal selection among candidate system designs. In order for this evaluation to take place in the early stages of system design, a projective workload assessment technique is required; therefore, a subjective technique must be implemented rather than physiological or performance measures.

Courtright and Kuperman (1984) employed both Pro-SWAT and SWAT in the operational test and evaluation of a complex multioperator, multistation military system. The rating scale was used in a field evaluation of a system requiring skilled personnel to operate semiautomated equipment. The SWAT rating scale was selected for this application for several reasons: it was an instrument that subjects could use repeatedly over a period of days, it could be quickly administered with minimal distraction on the part of the operators, it was scorable in terms of individual rating styles, and it demonstrated measurement precision for relatively small changes.

The evaluation took place in two states. First, two highly experienced operators used SWAT projectively to evaluate the completeness of the task taxonomy of events to be used in the field data collection. Thus, Pro-SWAT was used to guide the design of the field experiment. Second, 30 field evaluators used SWAT and 38 task categories to analyze the distribution of workload across work stations.

The SWAT instrument, as used in this application, demonstrated sensitivity in identifying problem tasks. In addition, the concepts of the instrument were found to be readily understandable and accepted as legitimate by the test community and the subjects. Courtright and Kuperman concluded that "... as a relatively simple, easily administered tool for examining the subjective workload associated with individual task performance, SWAT appears to be very useful" (Courtright and Kuperman, 1984).

PRO-SWAT

Due to the demonstrated reliability of SWAT as a measurement of operator workload, a similar technique, based on the predictive or projective application of SWAT (Pro-SWAT) has been developed for application at the predesign stage of system development. This measure of workload provides an opportunity to involve, in a unique way, the eventual user/operator of the system. The evaluation of workload that may accompany the use of a new technology is something the user is uniquely qualified to provide. Pro-SWAT asks the user to describe how a new technology and system design will impact workload, not how the system should be design (Eggleston and Kulwicki, 1984).

Pro-SWAT is based upon a combination of SWAT and another subjective technique known as Ground Attack Tactics Survey (GATS). GATS methodology consists of a structured interview technique that is used to identify workload "choke points" for operational air-to-ground attack missions (Greene, Arbak, Courtright, and O'Donnell, 1981). Detailed maps, charts, and mission scenarios are used to carefully talk pilots through a mission with detailed questioning to reveal tasks or subtasks that have excessively high workload.

Pro-SWAT, like SWAT, occurs in two stages. The scale development phase is identical to that used for SWAT. The event scoring phase, however, is replaced by a procedure derived from GATS methodology. The subject is required to imagine that he is experiencing events and performing appropriate tasks with either a known system or a hypothetical system. Reid et al. (1984) have reviewed the psychological literature pertaining to the use of mental imagery for skill acquisition and have concluded that subjects were able to accurately imagine the events they were attempting to learn. This is the same type of mental imagery that subjects are asked to perform as part of the Pro-SWAT rating procedure. Since previous experience is required in order for mental practice to be effective (Corbin, 1967), obtaining estimates of workload for systems which do not exist depends upon responses from "expert" subjects. No subjects will be available who have experience on a nonexistent system, so subjects having the most similar experience possible should be selected (Reid et al., 1984).

After the "expert" subjects have completed the scale development phase, they are provided with detailed information concerning the mission and details about operation of the conceptual system. This may include drawings and/or mock-ups. Special attention is given the description of procedures for operation of the system with precise detail on tasks and subtasks. Each subject is then talked through a representative but hypothetical mission, once using a current or baseline system and once for each conceptual system or design option. Pro-SWAT ratings are obtained at points of interest selected for their anticipated high workload or expected conceptual system superiority or inferiority. These ratings reflect the amount of time load, mental effort load, and psychological stress load that the operator thinks would be associated with the hypothetical event. The same events are rated for the baseline system and all conceptual systems in order to obtain relative workload information. As with SWAT, the scale values obtained from Pro-SWAT are interval level data. An additional advantage of Pro-SWAT is that the data are in the same metric as SWAT. If SWAT is used in later simulations and flight tests, direct comparisons can be made between the predictive results of Pro-SWAT and later real-time measurements.

Eggleston (1984) compared projected and measured workload ratings using Pro-SWAT and SWAT. The technique was used in a projective manner to estimate the workload implications of system configurations during the conceptual design state of development. Experienced aircrews were given descriptions of a basic and several enhanced versions of an advanced attack aircraft. They then used their knowledge and experience of similar missions to rate the level of time load, effort load, and psychological stress load expected to exist at selected points in the mission and for various system configurations. Another group of equally experienced aircrews participated in real-time simulation using the same system concepts and similar mission scenarios. Five system configurations and three mission segments were common to both the Pro-SWAT and SWAT task ratings. A Pearson coefficient of correlation of .85 was found between predicted workload ratings and those obtained in flight simulation, indicating a statistically reliable relationship between predicted and experienced workload. Eggleston concludes that, "given adequate materials and subject experience ... the workload associated with a system in its conceptual stage can be measured, and seems to be related to the workload experienced in similar simulated system/mission conditions. Specifically the pilots were able to perform the predictive task with a conceptual system, and their estimates of workload were not unlike those reported by other experienced pilots who, in a simulator, actually experienced essentially the same systems/missions" (Eggleston, 1984).

Pro-SWAT strongly suggests itself as a tool for application to the prediction of workload for advanced, conceptual weapon systems. It is sufficiently amenable to field use to support data collection away from the laboratory environment. It has been demonstrated, to a limited extent, to have predictive validity when compared against man-in-loop simulation.

Section 5
METHODOLOGY

PROCEDURE

Field data collection was conducted at the Army Aviation Center, Fort Rucker, Alabama, on 16 May 1984. Ten military and one civilian pilot served as subjects (Ss). All were familiar with the LHX program and several of them were assigned in direct support of it. A brief introduction to the VPD Technology Assessment Study was given, and the importance of obtaining estimates of probable workload was explained. The Ss were provided an overview (similar to that in Section 4) of the concepts of workload and its measurement/prediction, specifically by the Pro-SWAT method. The Ss then performed the card sorting by the Pro-SWAT method. The Ss then performed the card sorting task required for individual SWAT scale development. The MEP was next presented, emphasizing the information sources for the VPD-based crew systems (Section 2). The AFAMRL-developed mission scenario (Section 2) was briefed to them in detail. The baseline crew system concepts and the four options (Section 3) were explained in detail, using both viewgraphs and full size cardboard mock-ups. [Eggleston (1984), points out that if the Ss' orientation to the concepts and mission "is not of sufficient detail, then even an experienced subject may not be able to reliably judge workload."] At this point, the Ss were again led through the mission scenario and Pro-SWAT ratings were obtained at each of six distinct mission phases (identified below). In obtaining the Pro-SWAT ratings, the experimenter briefed the events and priorities of that segment. The Ss had a folder which contained illustrations of all five crew system concepts and a SWAT data collection form (Figure 7) for each alternative crew system. Each form was annotated to indicate the option being evaluated and the segment of the mission at which workload was to be estimated. The Ss were requested to project themselves into the mission and to estimate the level of workload that they believed they would encounter in attempting to accomplish mission tasks with each crew system concept. Following the pro-SWAT data collection, the Ss were requested to complete a series of rating scales which explored several qualitative aspects of crew system interface utility.

Lastly, the Ss were requested to describe what they felt an "ideal" VPD crew system would be.

SUBJECTS

The importance of using highly experienced Ss in the evaluation of advanced crewstation components was discussed in Section 4. Additionally, Kuperman (1984) addressed the requirement for selecting Ss for participation in the assessment of advanced aircraft crew system concepts who are sufficiently knowledgeable about both mission requirements and advanced avionics capabilities to minimize the need for extensive training. Kuperman et al. (1983) pointed out the particular importance of the Ss' experience in their evaluation of a derivative fighter aircraft which exploits advanced sensors and weapons.

Eleven Ss participated in the workload data collection exercise, ten military and one civilian. All military pilots were currently officers or warrant officers. The military pilots reported an average of approximately 8 years, 4 months of flying experience (minimum about 1 year and maximum over 15 years). (The civilian pilot reported a total of 313 hours of experience obtained in a variety of light aircraft.) Four pilots reported having flown helicopters in combat for an average of 775 hours (minimum 150 hours and maximum 1400 hours). The mean reported noncombat flying experience (military only) was 1443 hours (minimum 430 hours and maximum 3500 hours). All military pilots reported flight simulator experience with an average of approximately 214 hours (minimum 30 hours and maximum 600 hours).

The military pilots reported an average of approximately 742 hours flying NOE (minimum 20 and maximum 3000). Nine of them reported experience in flying at HOGE (mean approximately 318 hours, minimum 10 hours, maximum 1000 hours). The ten military pilots reported an average of approximately 238 hours of night flying experience (miminum 20 hours, maximum 600 hours). One S reported 800 hours of experience in performing day A/G attack missions and 500 hours in night A/G.

Subject Name ____________

Display Configuration: ____________

Mission Segment: ____________

INSTRUCTIONS: For each of the three sections below, check the one box (1, 2, or 3) that you feel applies. Be sure to complete all three ratings.

TIME LOAD

☐ (1) Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.

☐ (2) Occasionally have spare time. Interruptions or overlap among activities occur frequently.

☐ (3) Almost never have spare time. Interruptions or overlap among activities are very frequent, or occur all the time.

MENTAL EFFORT

☐ (1) Very little conscious mental effort or concentration required. Activity is almost automatic, requiring little or no attention.

☐ (2) Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredicability, or unfamiliarity. Considerable attention required.

☐ (3) Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.

PSYCHOLOGICAL STRESS

☐ (1) Little confusion, risk, frustration, or anxiety exist and can be easily accommodated.

☐ (2) Moderate stress due to confusion, frustration, or anxiety noticeably adds to workload. Significant compensation is required to maintain adequate performance.

☐ (3) High to very intense stress due to confusion, frustration, or anxiety. High to extreme determination and self-control required.

Figure 7. (Pro-)SWAT Data Collection Form

Six of the Army pilots were current in the UH-1 and the remaining four were current in the AH-1. Four reported experience with guided A/G weapons, three with HUD-equipped aircraft, two with FLIR, two with MFPK, one with a moving map display, one with MFDs, one with voice control subsystems, and one with night vision goggles.

Overall, the Ss were a highly experienced group of aviators. They were very familiar with low altitude operations (NOE and HOGE) and familiar with night flying. They reported only limited experience with technologies comparable to those in the LHX/SCAT MEP (which is not surprising since aircraft with similar equipment are only now entering the Army operational inventory).

INDEPENDENT VARIABLES

Options

The five crew system concepts for which Pro-SWAT (and qualitative rating scale) data were collected are described in Section 3. The VPD technology exploited in each concept were:

a. Baseline: 20-degree V by 30-degree H HUD

b. Option 1: 30-degree V by 40-degree H monocular HMD

c. Option 2: 60-degree V by 90-degree H binocular HMD

d. Option 3: 60-degree V by 120-degree H stereo, binocular HMD

e. Option 4: 120-degree V by 220-degree H cockpit-mounted VPD

Mission Segments

Pro-SWAT data were collected at six points during the mission scenario. They were:

a. Cruise: During the outbound mission segment between the base and the refueling point, the crewmember is relatively unburdened. Once the airborne formation has been adopted and system checks have been performed, the only concerns are maintaining inflight formation and performing contour flight and navigation. No threats are expected.

b. Pre-FLOT: Immediately before crossing into enemy territory, the LHXs perform final system checks and weapons arming. Roles within the flight (scout/SEAD, combat security, and antiarmor) are adopted.

c. Ingress: The flight is transversing enemy territory at low altitude. Chance encounters with threat systems are highly probable. Navigation is between the trees and below the hills and ridges, to make maximum use of terrain masking.

d. Approach to Battle Position: Encounters with enemy threats are becoming more likely. Priority is switching from navigation to target search and acquisition.

e. Air-to-Ground Engagement: Targets are being acquired, missiles locked, and tanks destroyed. SAMs and AAA, intermixed with the tanks, are being engaged and defeated.

f. Air-to-Air Engagement: Priority has been changed from antiarmor, scout/SEAD, or combat security to antiair. Enemy helicopters must be destroyed while ground-to-air threats are defeated.

DEPENDENT VARIABLES

Pro-SWAT

The Pro-SWAT rating instrument was applied for each of the five options at each of the six mission segments. The procedure for collecting Pro-SWAT data is described above.

Rating Questionnaires

In addition to the Pro-SWAT data collection sheets, the Ss were asked to provide rating data along several qualitative scales regarding their impressions of some aspect of each of the crewstation configurations. A seven point scale was used throughout, with a lowest rating (1) having a semantic anchor of "prohibit," "prevent," or "rejected" while the highest rating (7) carried a semantic anchor of "enable" or "accepted/desired." (An example of the questionnaire is presented in Appendix A.)

The first question dealt with the perceived ability of the concept to support the acquisition and maintenance of battlefield situational awareness. The second rating dimension dealt with the contribution of the crew system to overall mission effectiveness. A group of six rating scales explored the performance of major functional crew tasks (pilotage, navigation, communications, target acquisition, weapon delivery, and survivability). The last question asked about the expected degree of acceptance of the Army pilot community for each crew interface concept. In addition to providing the ratings, the Ss were requested to provide supporting comments. (All comments, arranged by rating dimension and broken down by option, appear in Appendix B).

"Ideal" Crew Interface Design

The administration of the Pro-SWAT and rating scale instruments was followed by a roundtable discussion which covered the MEP, the LHX/SCAT mission, and the crew system concepts. Following this group discussion, the Ss were asked to individually sketch out what they felt would be the optimum or "ideal" cockpit layout.

Section 6
ANALYSIS AND RESULTS

GENERAL

This section of the report is divided into three parts. First, the Pro-SWAT data analysis procedure is described and the resulting data are presented in the form of tables and graphs. Next, a similar treatment of the subjective rating scale instrument is provided. Last, the "ideal" LHX VPO configuration, as defined by the Ss, is depicted.

PRO-SWAT

The Pro-SWAT methodology employs a three-dimensional matrix (time stress, mental effort, and psychological stress) within which to quantify workload. A unidimensional scale is desired for ease in making comparisons between various reports of workload. The procedure for performing this transformation is graphically depicted in Figure 8 and described in Reid et al. (1981). The procedure employs a conjoint measurement technique to construct an interval level workload scale from ordinal rankings of combinations of levels on the three workload dimensions.

Development of Individual Workload Scales

An interval scale is developed for each S. A randomly ordered set of cards containing all possible combinations (one combination on each card) of the three rankings of the three SWAT dimensions ($3^3 = 27$) is sorted by each S so as to rearrange them in a sequence from least through greatest workload. Thus, a 1,1,1 triplet ranking would represent the lowest level of workload and a 3,3,3 triplet, the highest. It is the arrangement of the intervening combinations that reflects the S's individual perception of workload. For example, some Ss are acutely sensitive to time stress and arrange the deck to reflect time as an "outer loop." Thus, their arrangement would tend to associate higher levels of workload with moderate and low time stress ratings than corresponding (or perhaps higher) levels of the other two dimensions.

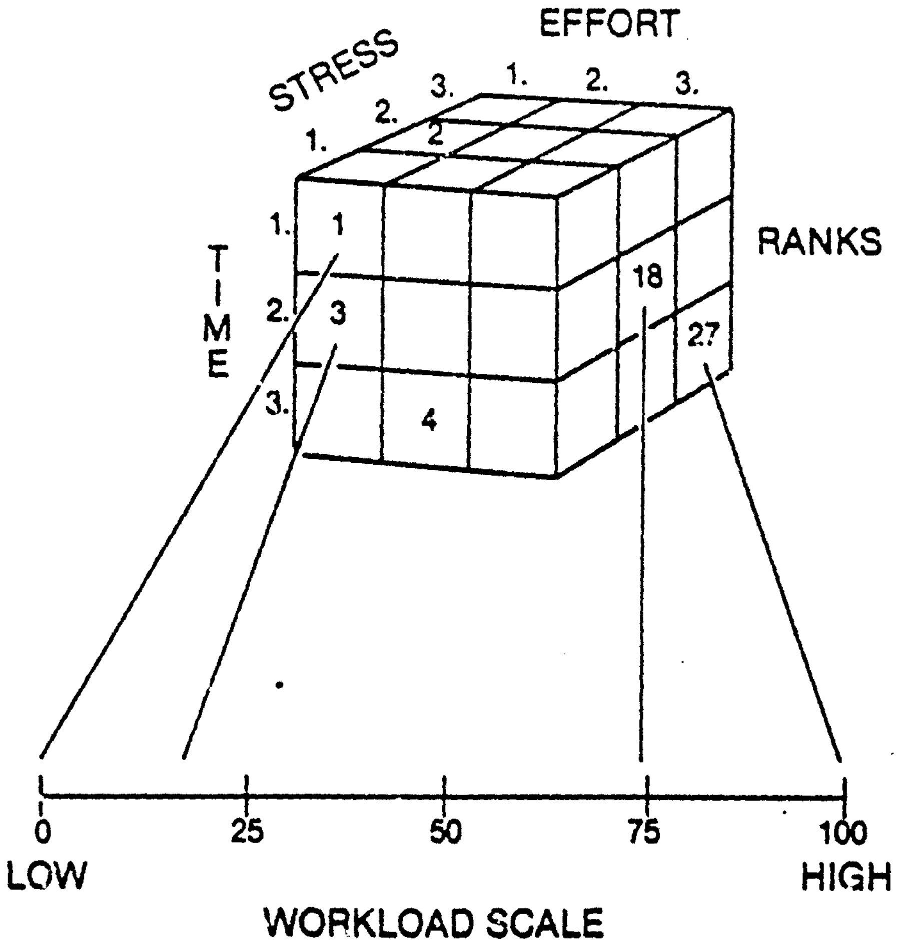

Figure 8. SWAT Individual Scale Development

All 11 Ss performed the SWAT card sort task. Three of these 11 produced sorts that contained too many errors (inconsistencies) to permit application of their individual scales. (For example, an S might rate a 2,3,1 as easier than a 2,1,1.) Of the remaining eight Ss, four were analyzed as being time stress dominated, two reflected a combination of mental effort and psychological stress, one a combination of mental effort and time stress, and one was dominated by psychological stress. These four prototypical interval scales were used in processing the reported Pro-SWAT scores for analysis. Table 3 presents the four prototypes used.

The table is used to convert the reported triplets into the unidimensional workload scores. The left-most column contains all possible triplets. The four other columns are the four scale prototypes. For each raw score triplet, the workload value is read from the same row in the column of the appropriate prototype. Thus, 2,2,2 reported by a time stress dominated individual would produce a workload value of 53.2.

Analysis of Variance

Figure 9 graphically presents the results of the Pro-SWAT data collection. The six mission segments, arranged in the order of increasing mean workload, are identified on the abscissa. The mean workload for each of the five crew system concepts is plotted for each segment. The data points for each concept are joined by line segments to assist in differentiating between options. Each point is the mean of the responses of the eight Ss. Table 4 presents the means that are plotted in the figure, together with respective standard deviations. The minimum expected workload has a Pro-SWAT rating of 13.9 (performing cruise using the Option 4 VPD) and the maximum observed is 93.2 (performing A/G attack using either the Baseline or the Option 1 VPD concept). As may be seen from the figure and table, the Ss' mean expectation of workload never increases as the crew systems progress from the baseline to Option 4. Three cases of identical expected mean workload levels occur, all involving the baseline and Option 1.

Three questions suggest themselves in considering the utility of the data to the operational command:

TABLE 3. PRO-SWAT PROTOTYPES

Triplet (T,M,P)*	T	M/P	M/T	P
1,1,1	0.0	0.0	0.0	0.0
1,1,2	9.6	25.2	1.6	39.7
1,1,3	20.2	32.9	6.3	70.0
1,2,1	7.9	27.1	40.4	13.7
1,2,2	17.6	52.3	42.0	53.4
1,2,3	28.1	60.0	46.7	83.7
1,3,1	17.1	43.6	72.0	22.8
1,3,2	26.8	68.8	73.6	62.4
1,3,3	37.3	76.5	78.3	92.8
2,1,1	35.6	2.2	13.7	4.7
2,1,2	45.3	27.4	15.3	44.4
2,1,3	55.8	35.1	20.0	74.7
2,2,1	43.5	29.3	54.0	18.4
2,2,2	53.2	54.5	55.7	58.1
2,2,3	63.8	62.2	60.4	88.4
2,3,1	52.7	45.7	85.6	27.4
2,3,2	62.4	70.9	87.3	67.1
2,3,3	73.0	78.7	91.9	97.5
3,1,1	62.1	23.5	21.7	7.2
3,1,2	72.3	48.7	23.3	46.9
3,1,3	82.9	56.4	28.0	77.2
3,2,1	70.6	50.6	62.1	20.9
3,2,2	80.2	75.8	63.7	60.6
3,2,3	90.8	83.5	68.4	91.0
3,3,1	79.8	67.1	93.7	30.0
3,3,2	89.4	92.3	95.3	69.7
3,3,3	100.0	100.0	100.0	100.0

*T = Time Stress
M = Mental Effort
P = Psychological Stress

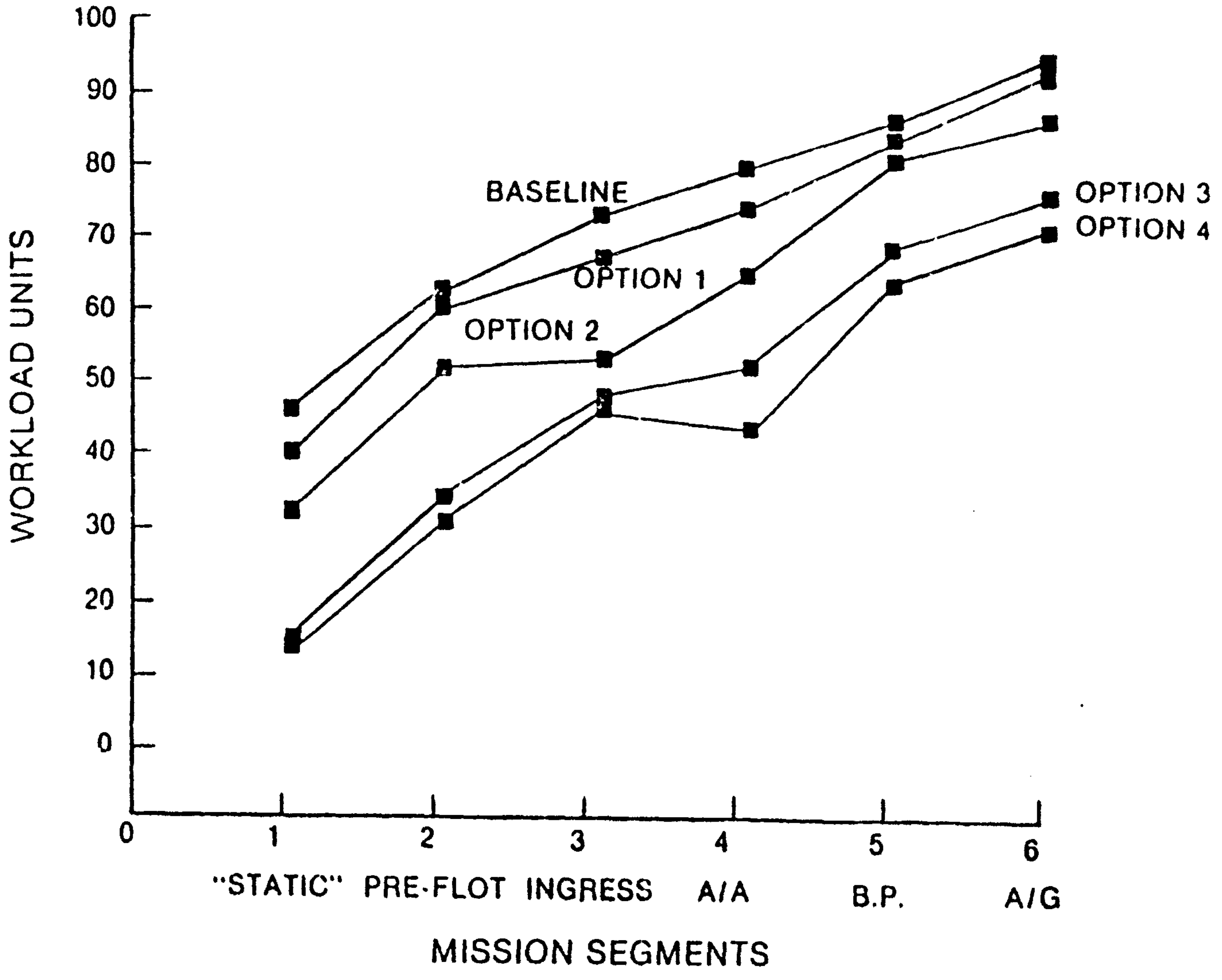

Figure 9. Graphic Summary of LHX Workload

TABLE 4. PROJECTED WORKLOAD, BY VPD CONCEPT AND MISSION SEGMENT (Means and Standard Deviations)

Mission Segment	Baseline	Option 1	Option 2	Option 3	Option 4
Cruise					
mean	45.8	38.0	32.1	15.1	13.9
std. dev.	33.8	34.5	23.6	22.5	16.5
Pre-FLOT					
mean	59.7	59.7	49.7	34.0	31.0
std. dev.	29.7	25.9	13.1	26.9	22.7
Ingress					
mean	71.3	67.5	51.8	48.1	46.3
std. dev.	32.0	30.1	25.0	21.0	20.2
A/A					
mean	77.2	73.9	63.1	52.2	43.6
std. dev.	22.0	22.3	31.4	34.0	35.4
App. to Battle Position					
mean	84.3	84.3	79.9	68.6	64.4
std. dev.	19.6	19.6	17.3	17.5	19.9
A/G					
mean	93.2	93.2	85.8	76.1	72.1
std. dev.	13.7	13.7	17.8	20.2	17.7

a. Is there a wide variation in workload to be expected within the LHX/SCAT mission? (Are the mission segment expectations of mean workload significantly different from each other?)

b. Do any of the five VPD-based crew system interface concepts offer opportunities for reducing this workload? (Are the concepts significantly different from each other?)

c. Are some concepts better at supporting reduced workload during some mission segments than during other? (Is their a significant interaction between concepts and mission segments?)

These questions were used to guide the analysis plan.

Table 5 presents a summary of an analysis of variance of (ANOVA) (SAS, 1982, Process ANOVA) in which the Pro-SWAT workload estimates serve as the dependent variable.

TABLE 5. ANALYSIS OF VARIANCE: PROJECTED WORKLOAD

Source of Variation	SS	DF	MS	
Concepts (C)	27245.0	4	6808.9	$p \leq 0.01$
Mission Segments (S)	79675.0	5	15932.8	$p \leq 0.01$
C x S	1659.7	20	82.0	N.S.*
Error	123052.0	210	586.0	
Total	231631.6	239		

*N.S. = Not Significant

The main effect, Concepts, is found to be highly statistically significant. This is equivalent to rejecting the hypothesis that the five VPD crew systems are equal to each other. (That is, at least some of the concepts are different from each other.) The main effect of Mission Segments is found to be of high statistical significance. This is equivalent to rejecting the hypothesis that workload is not expected to vary over the entire LHX/SCAT mission. (That is, at least some segments can be expected to result in higher workload levels than can other segments.) The interaction between Concepts and Segments is not statistically significant. This is equivalent to failing to reject the hypothesis that some Concepts can be expected to result in lower workload at some Segments, compared to other Concepts, but that the reverse would be true at other Segments. (That is, if one Concept is expected to support lower workload during one Segment than another Concept, then the first Concept will never result in higher workload than the second Concept at any other Segment.)

In Figures 10 through 15, the mean expected workload, pooled over the eight Ss, is shown in the form of bar graphs for each mission segment. Inspection of each graph shows that, as the options progress from the baseline to Option 4, expected workload never increases.

Figure 16 presents a graph of the means of the expected workload for each concept (pooled over Ss and mission segments). The generally monotonically decreasing form of the graph is apparent. Below the graph, the arrows, joined by horizontal lines, delimit the significantly different groupings (SAS, 1982, Process ANOVA, Means/Tukey) of the concepts as found by Tukey's Honestly Significant Difference (HSD) statistic. The baseline, together with Options 1 and 2, form one group; Options 2 and 3 form a second; and Options 3 and 4 form a third group. The lines joining the arrows permit comparisons between pairs of options. Any two options for which there is no common line beneath them are statistically different from each other (e.g., Options 1 and 3 are not equal).

Figure 17 presents two line graphs. The range of each graph is the 0 to 100 range of Pro-SWAT workload. The 30 mean expected workload levels (five concepts x six segments, pooled over eight Ss) are plotted on the lower graph. The mean expected workload levels for each of the eight Ss are plotted on the upper graph. Workload appears to be relatively evenly distributed along the lower graph. Six of the Ss' means cluster at the SWAT value of approximately 60, a seventh S exhibits a much lower mean (41.4), and the eighth S exhibits a much higher mean (75.4). (A Tukey's HSD test, performed as a post hoc test, revealed that only the Ss producing the highest and lowest

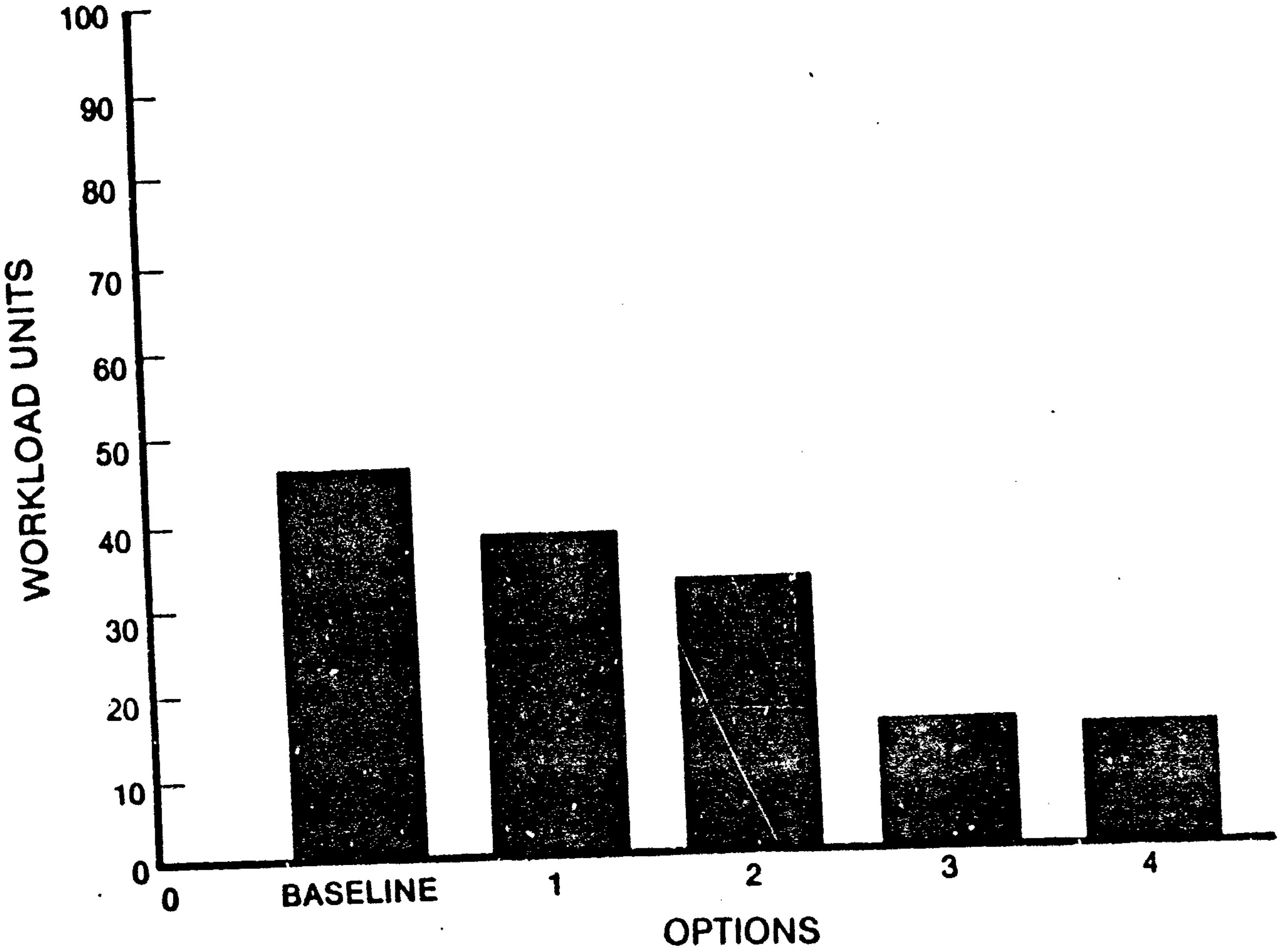

Figure 10. LHX Workload--Cruise

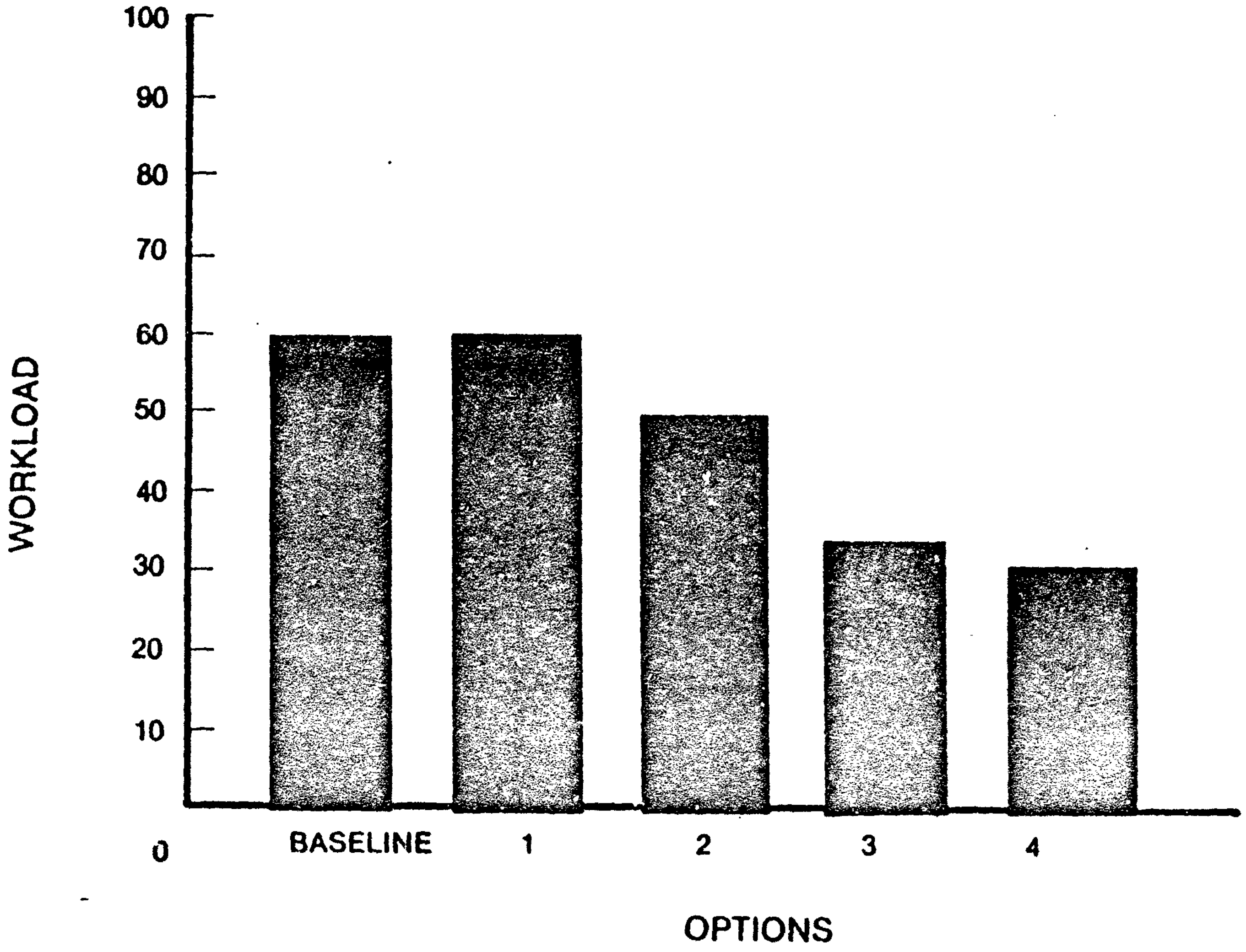

Figure 11. LHX Workload--Pre-Flot

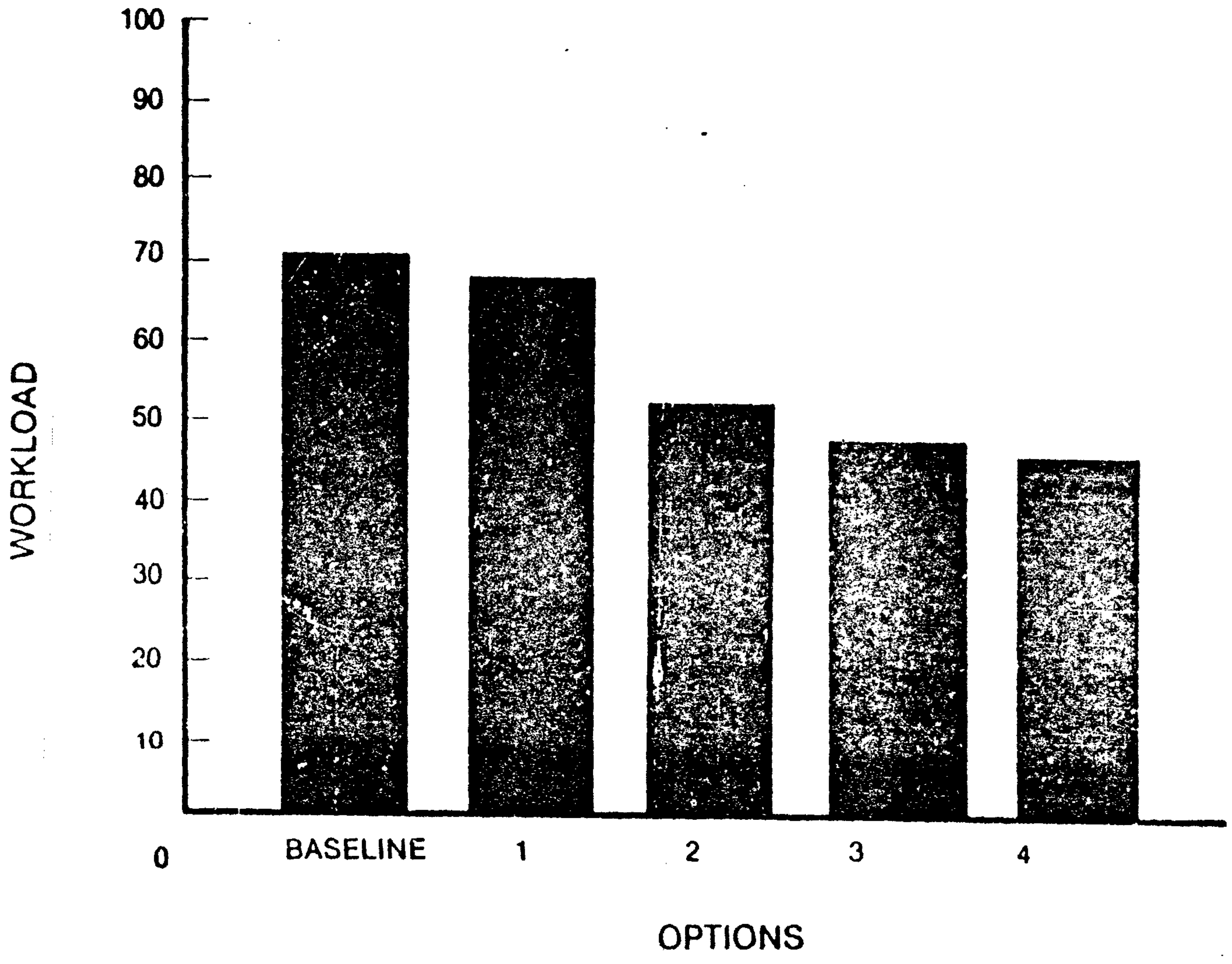

Figure 12. LHX Workload--Ingress

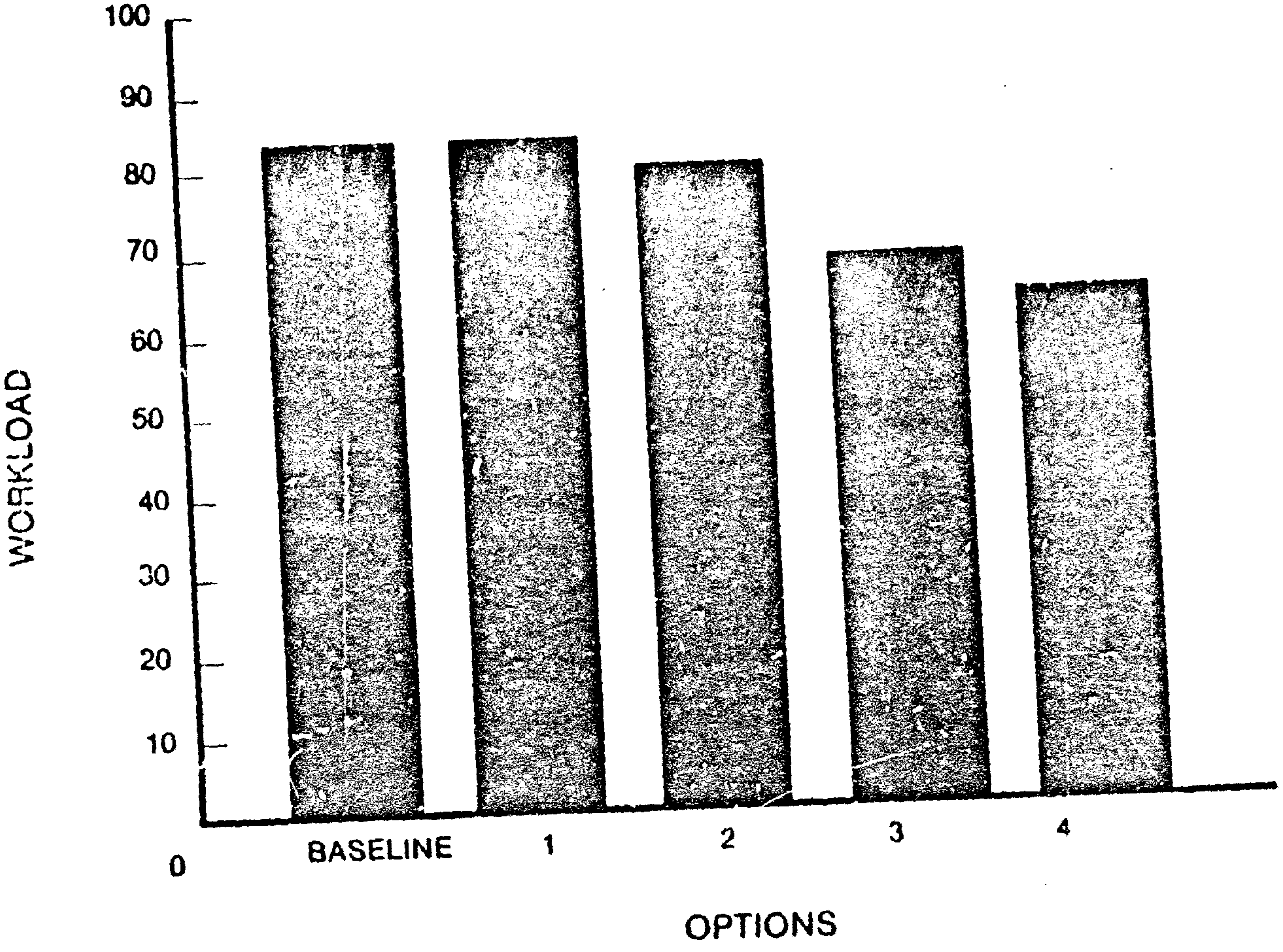

Figure 13. LHX Workload--Approach to B.P.

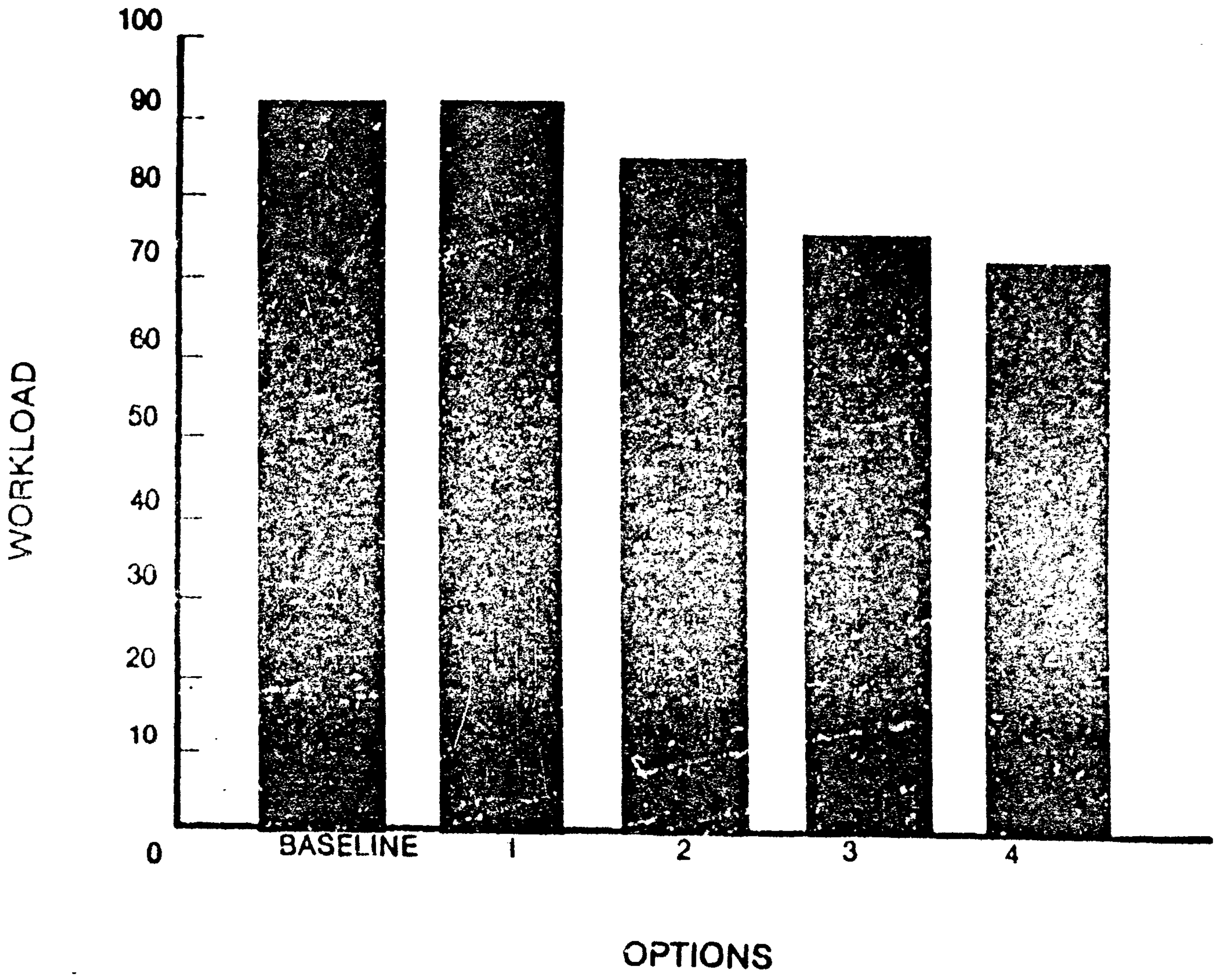

Figure 14. LHX Workload--A/G

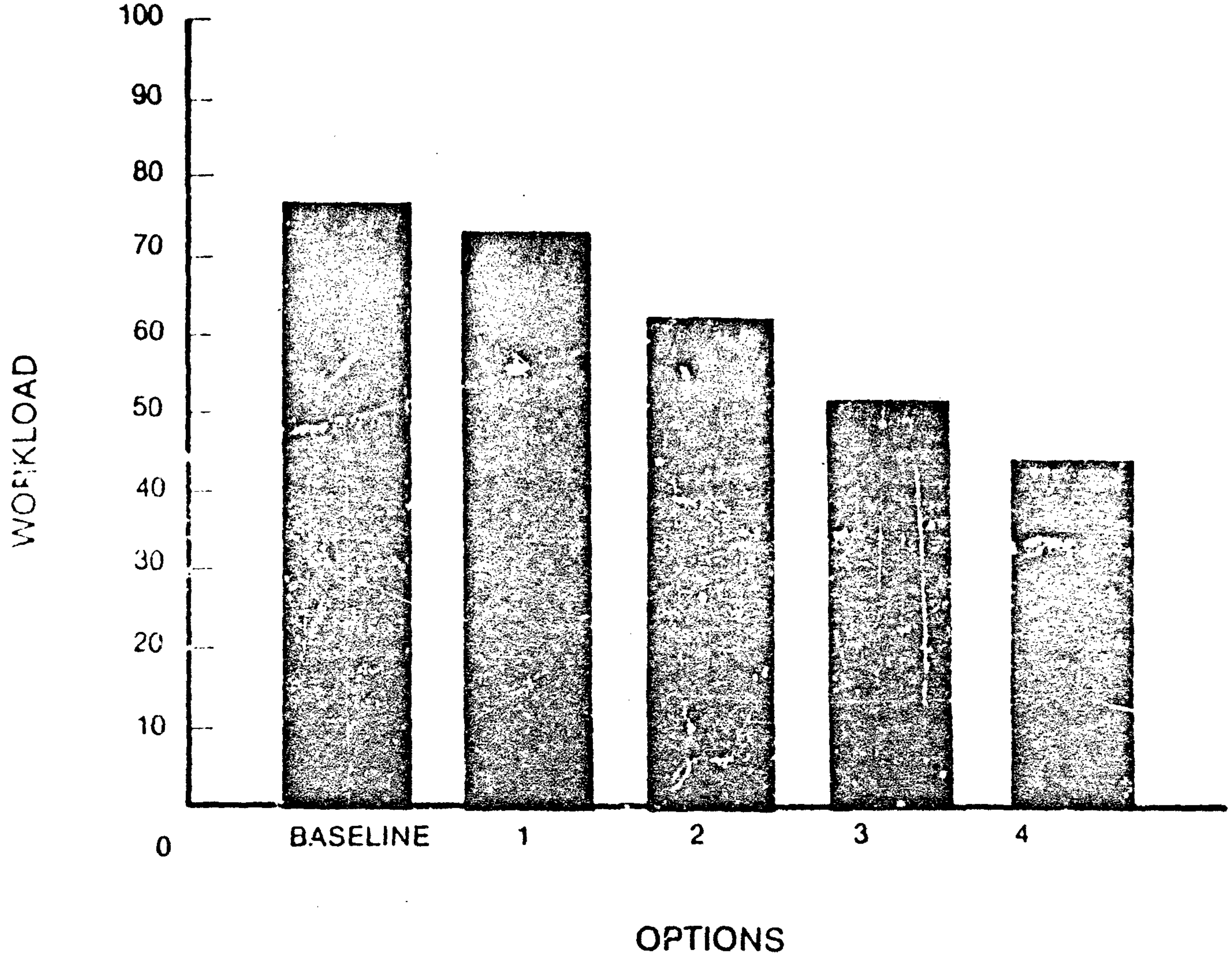

Figure 15. LHX Workload--A/A

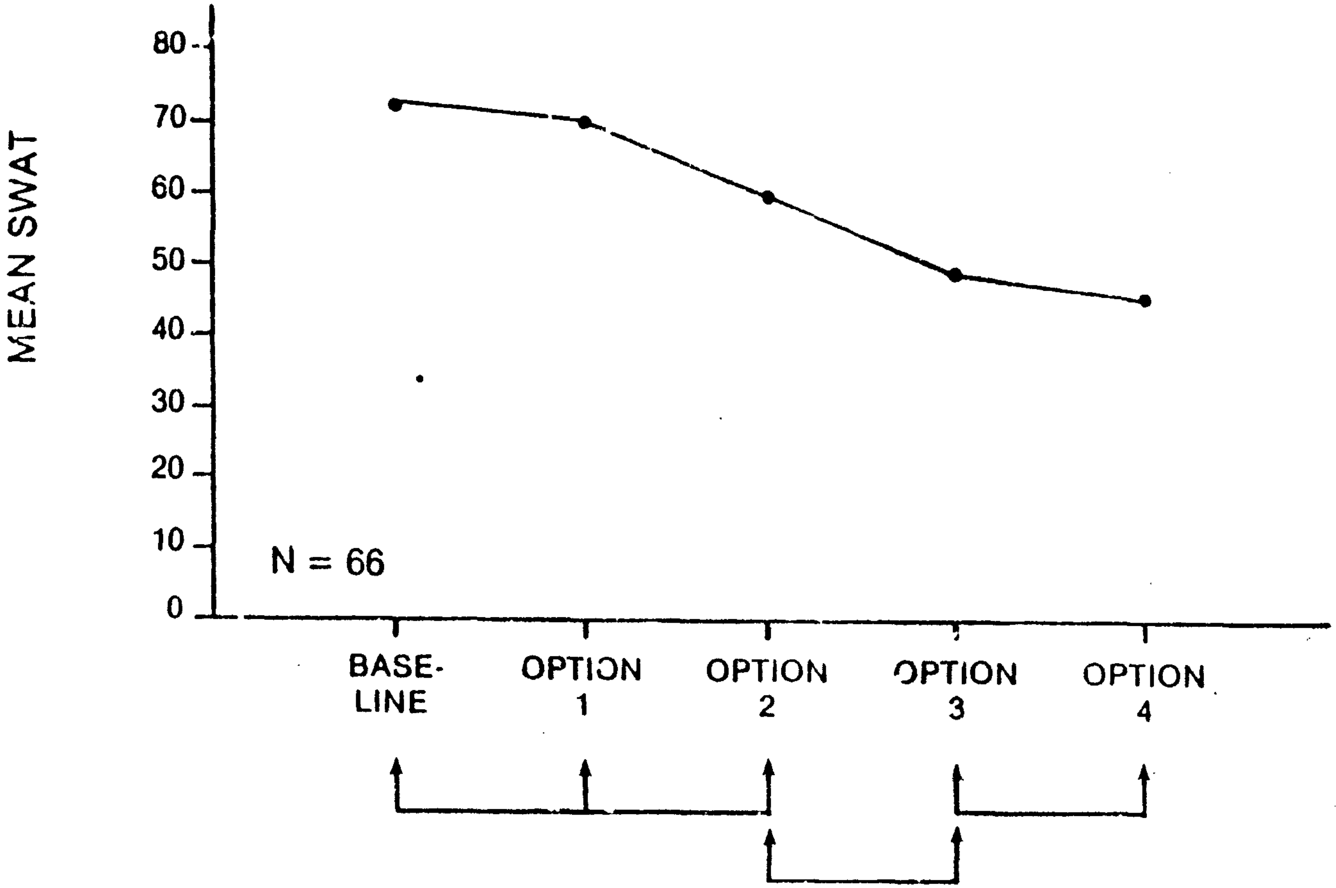

Figure 16. Tukey's Studentized Range (HSD) Test: Options (SWAT Pooled Over Mission Segments and Subjects)

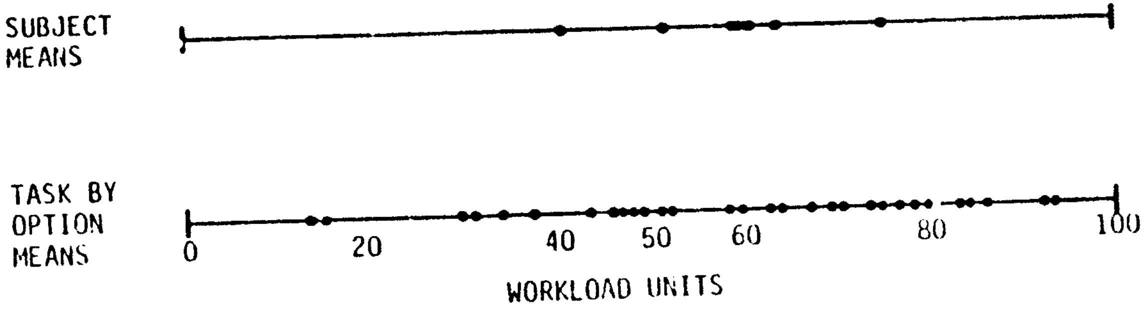

Figure 17. Graphic Comparison of Subject Means (SWAT)

mean Pro-SWAT values were significantly different from each other but that neither of them was significantly different from the six other Ss.)

SUBJECTIVE RATING QUESTIONNAIRES

All 11 Ss completed rating questionnaires (described in Section 5 and presented in Appendix A). All questionnaire data were analyzed by the same procedure. First, the ratings were transformed (SAS, 1982, Procedure RANK) into rankings. Thus, the seven-point rating responses were remapped onto a 0 to 54 range (five concepts x 11 Ss), equal interval ranking scale. An ANOVA (SAS, 1982, Procedure ANOVA) was performed for each question. In every case, the concepts were found to be highly significantly different from each other ($p \leq = 0.01$). Also for each question, Tukey's HSD test (SAS, 1982, Procedure ANOVA, MEANS/Tukey) was applied to explore the nature of the significance.

Figures 18 through 26 present mean results of rankings for each of the nine questions in the form of bar graphs. Beneath each bar graph, results of Tukey's HSD test are shown by the joined arrows which depict groupings of the concepts. The overall results are that, for every question, the baseline and Option 1 were never found to be distinguishable from each other; Options 3 and 4 are never distinguishable from each other; and with only one exception (the question dealing with communications), the baseline and Option 1 (as a group) are always different from Options 3 and 4 (as a group).

Comments were solicited from the Ss to substantiate their rating assignments. These comments are presented in Appendix B, arranged by concept, for each question.

"IDEAL" CREW INTERFACE

Figure 27 presents a synthesis of the "ideal" LHX/SCAT crew system interface, as depicted or described by the 11 Ss. It closely resembles Option 4. In general, the Ss desired that specific types of informational formats (e.g., weapons load/status) be available for display, on demand and at preselected locations, within the very wide FOV display.

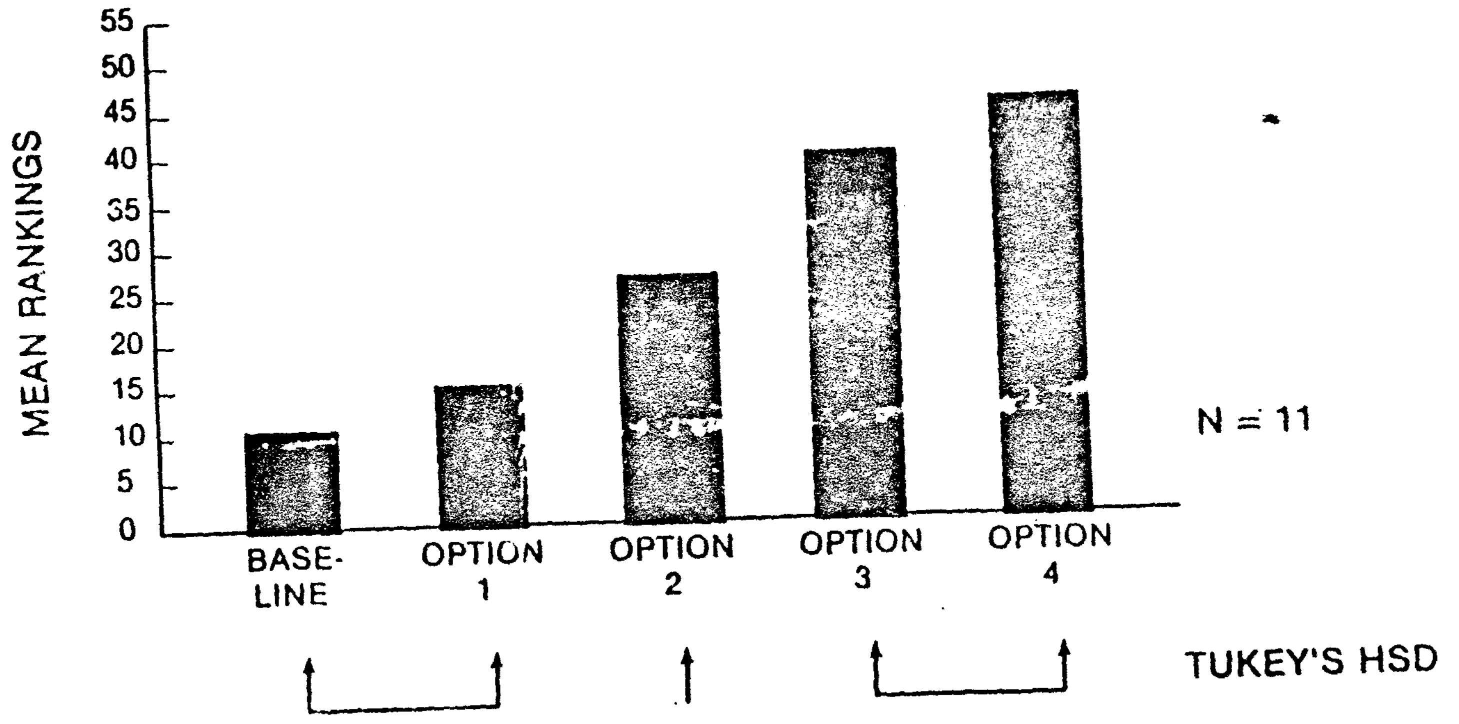

Figure 18. Ranking Data: Situation Awareness

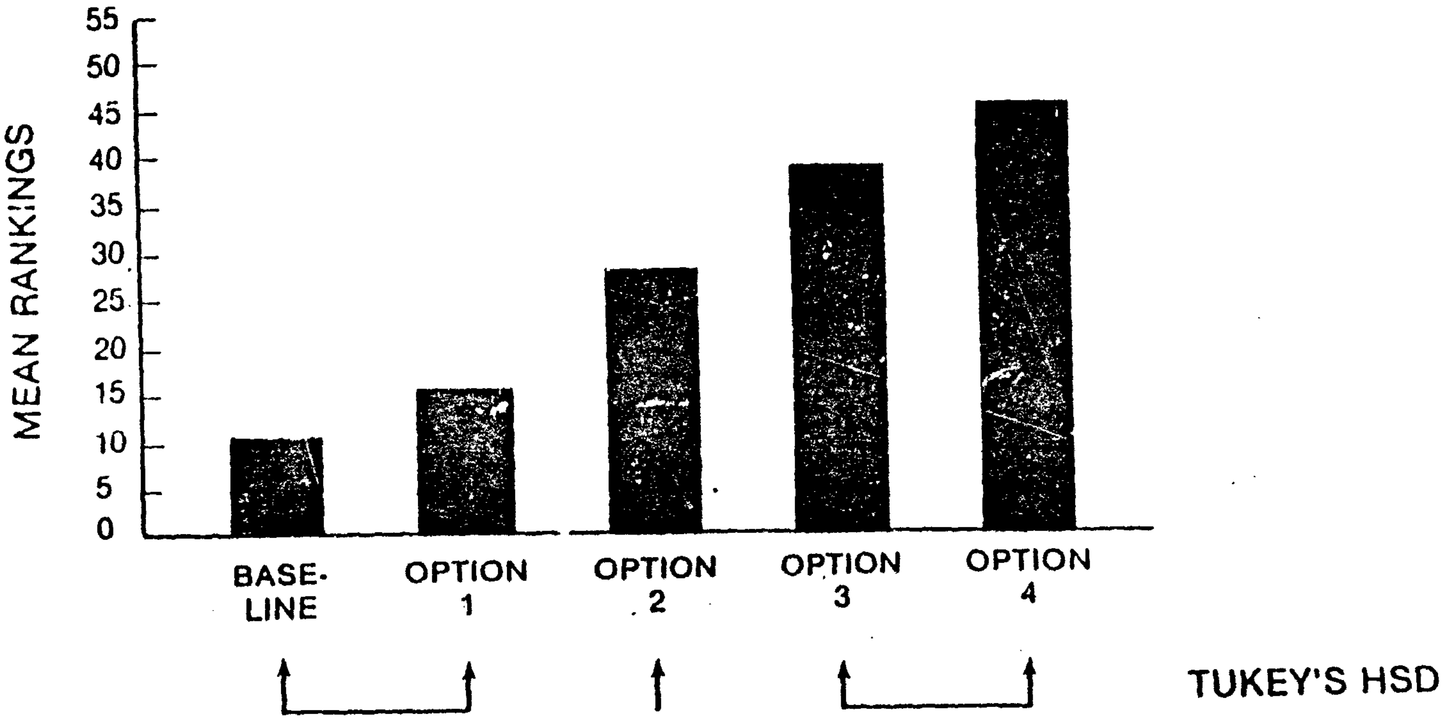

Figure 19: Ranking Data: Mission Effectiveness

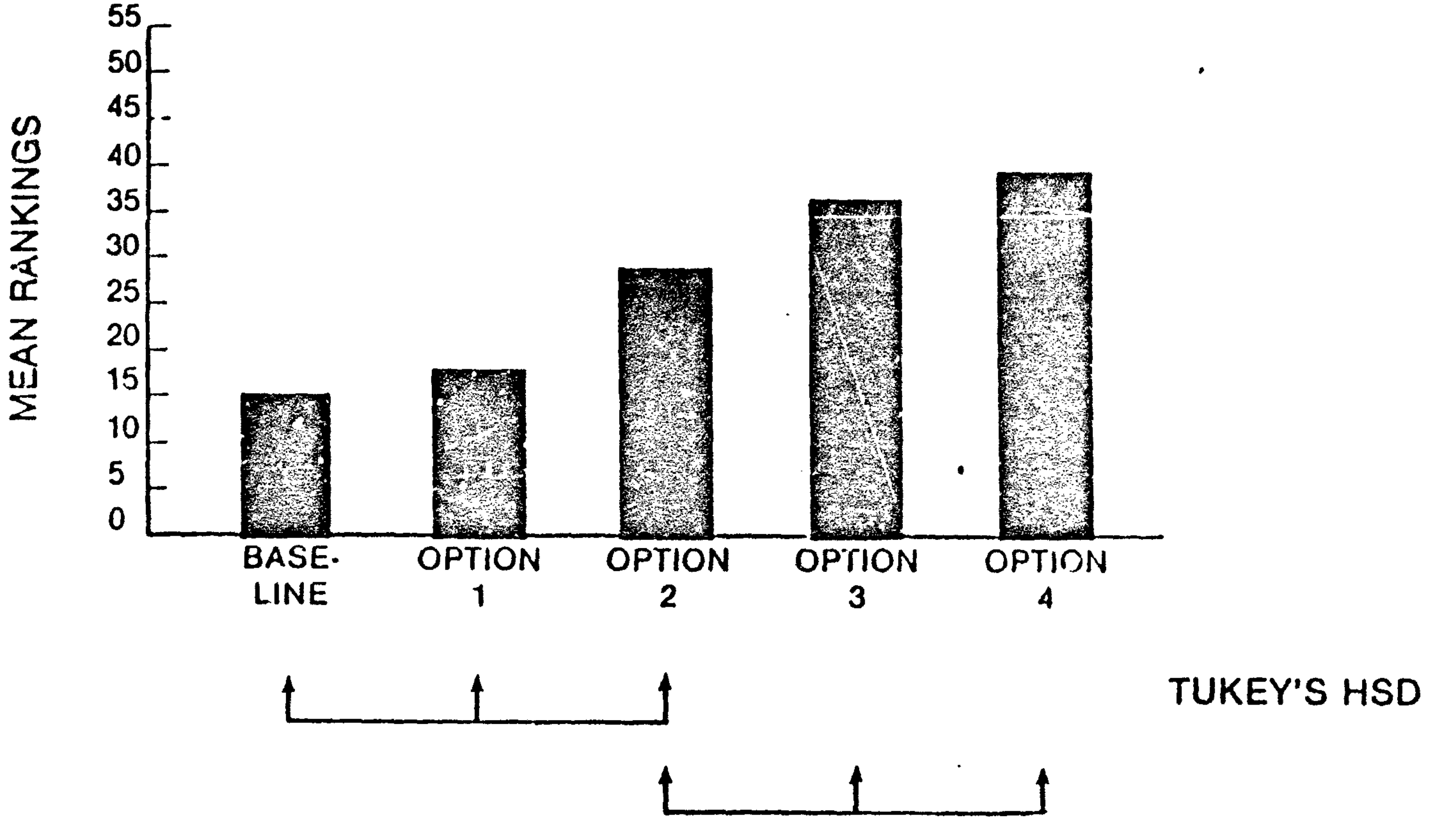

Figure 20: Ranking Data: Pilotage

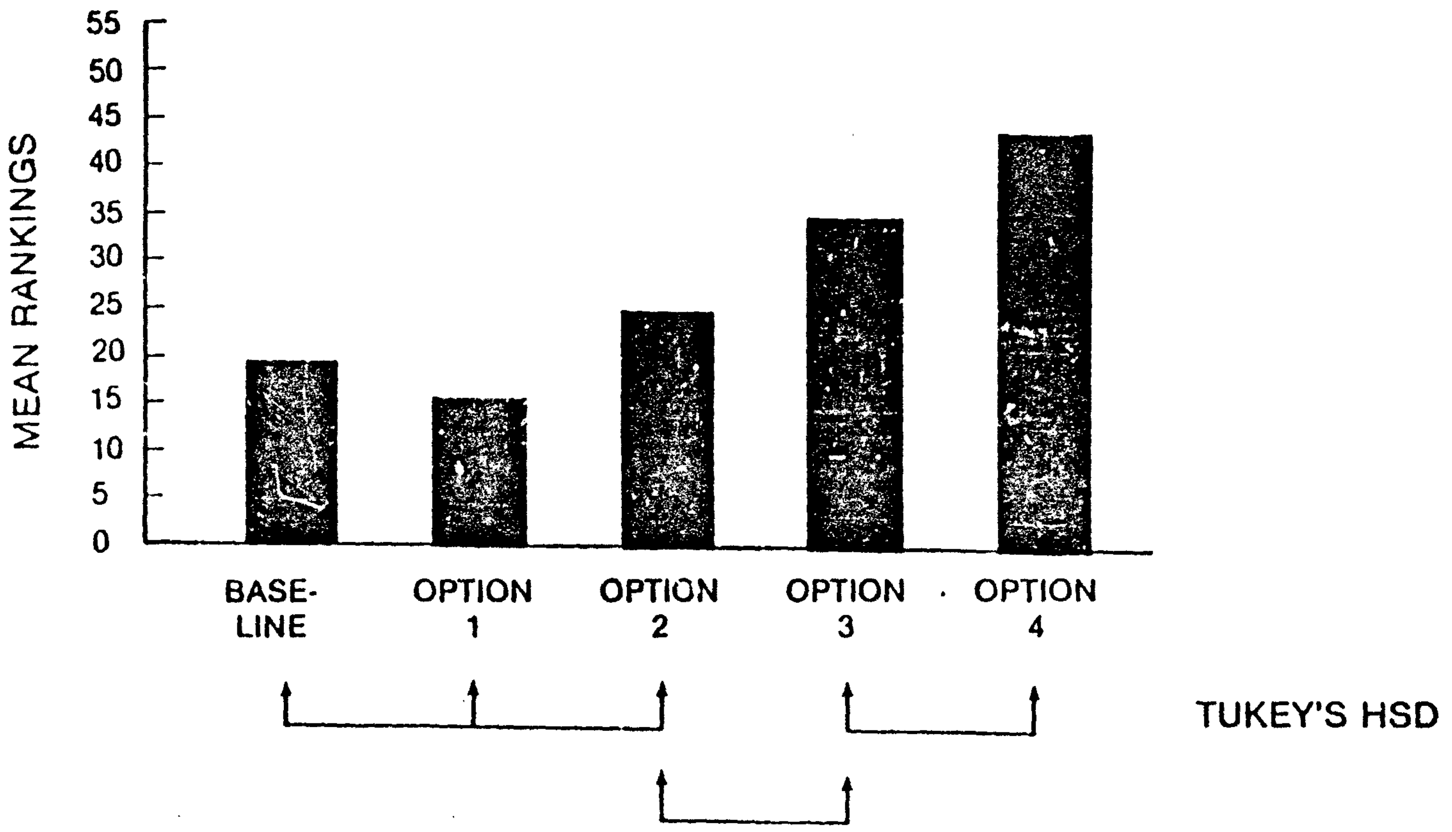

Figure 21. Ranking Data: Navigation

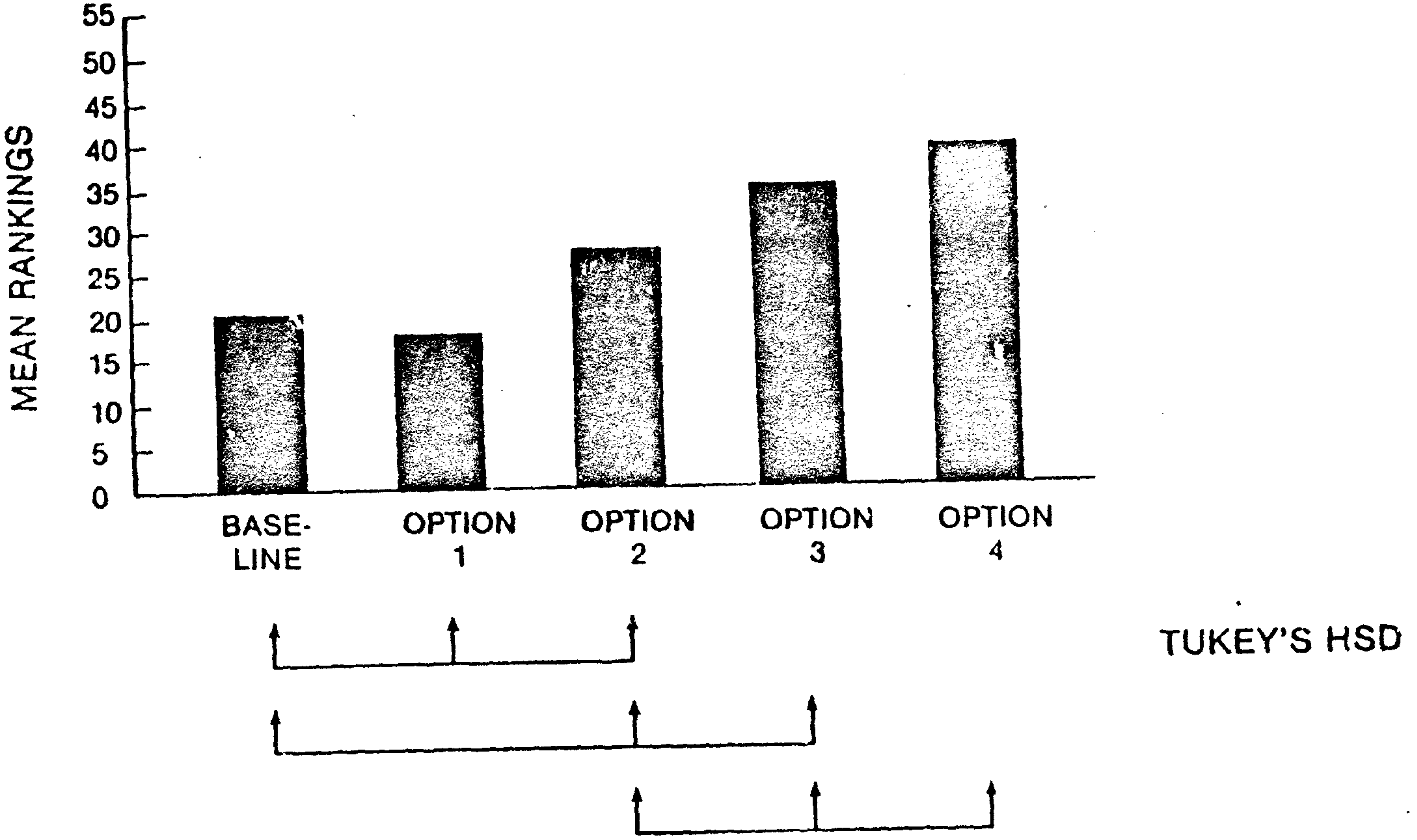

Figure 22. Ranking Data: Communications

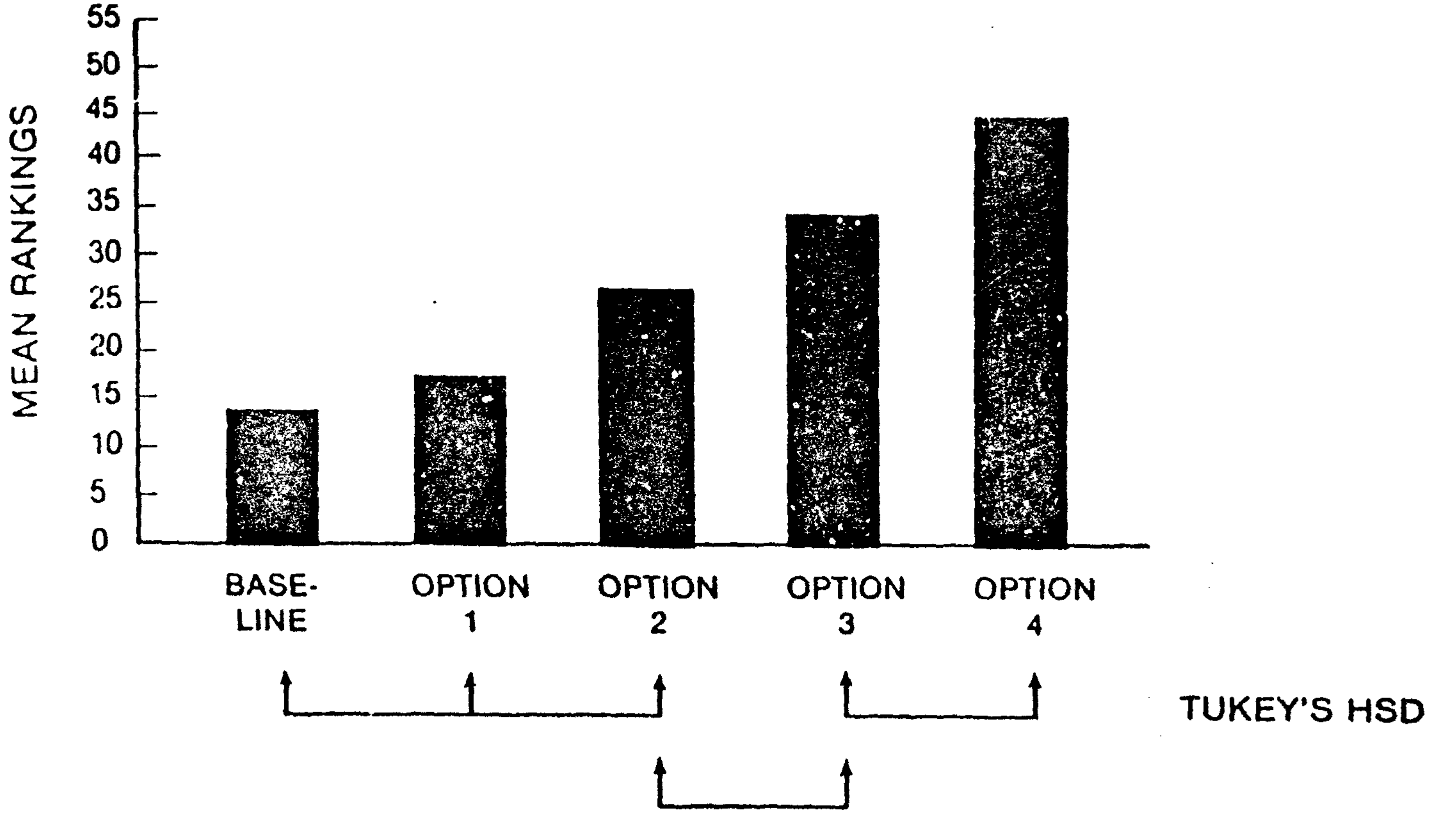

Figure 23. Ranking Data: Target Acquisition

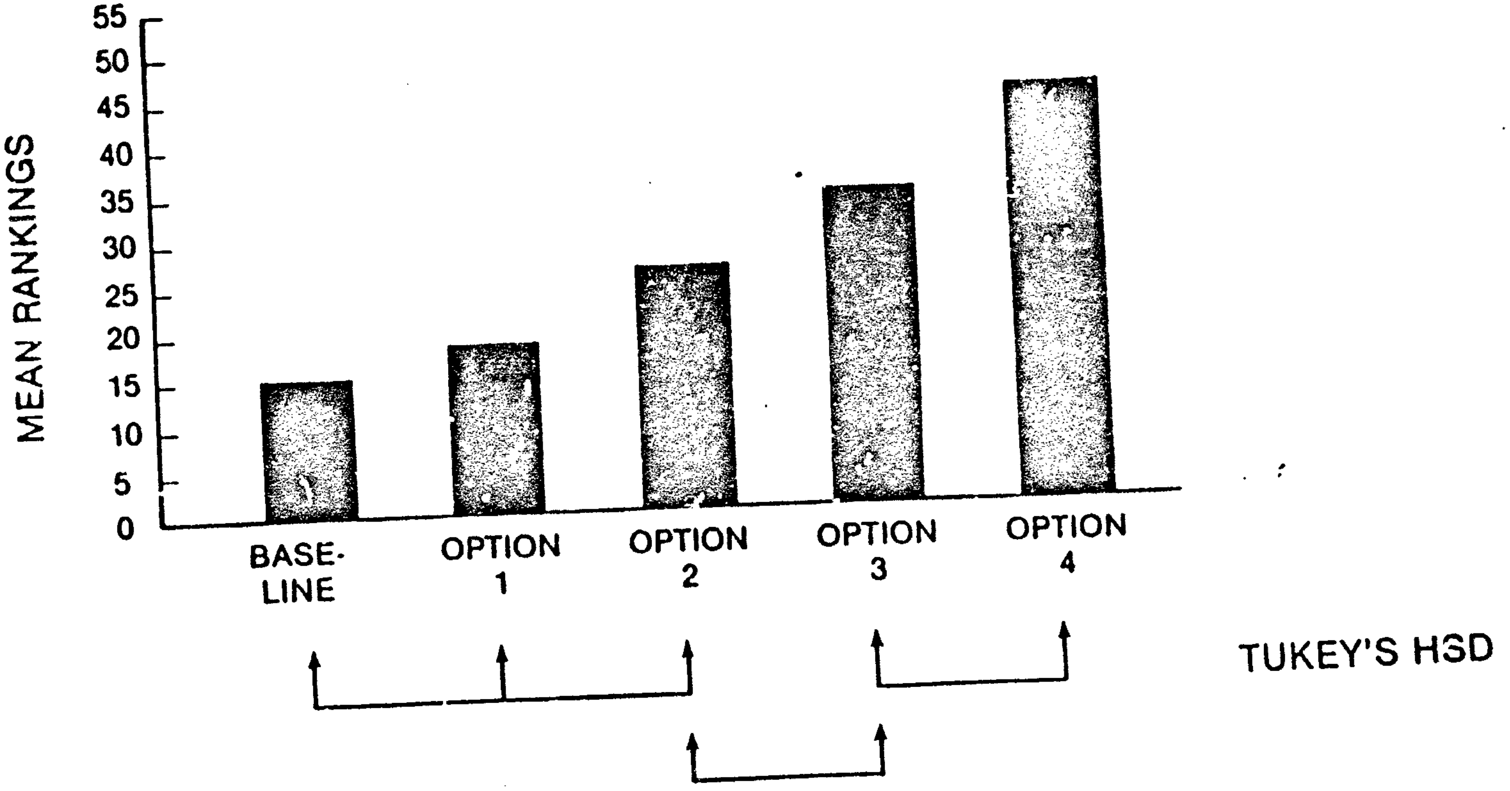

Figure 24. Ranking Data: Weapon Delivery

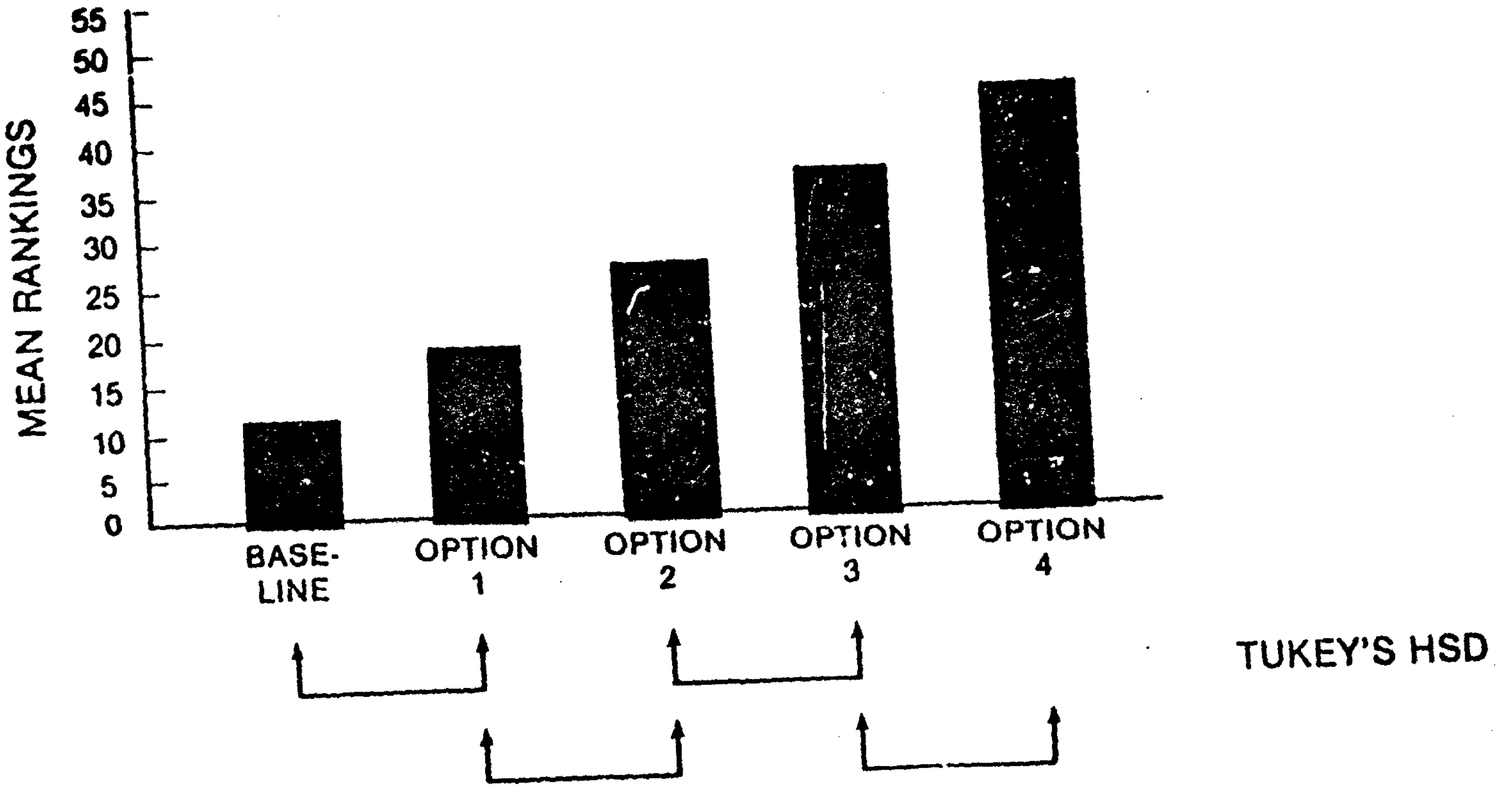

Figure 25. Ranking Data: Survivability

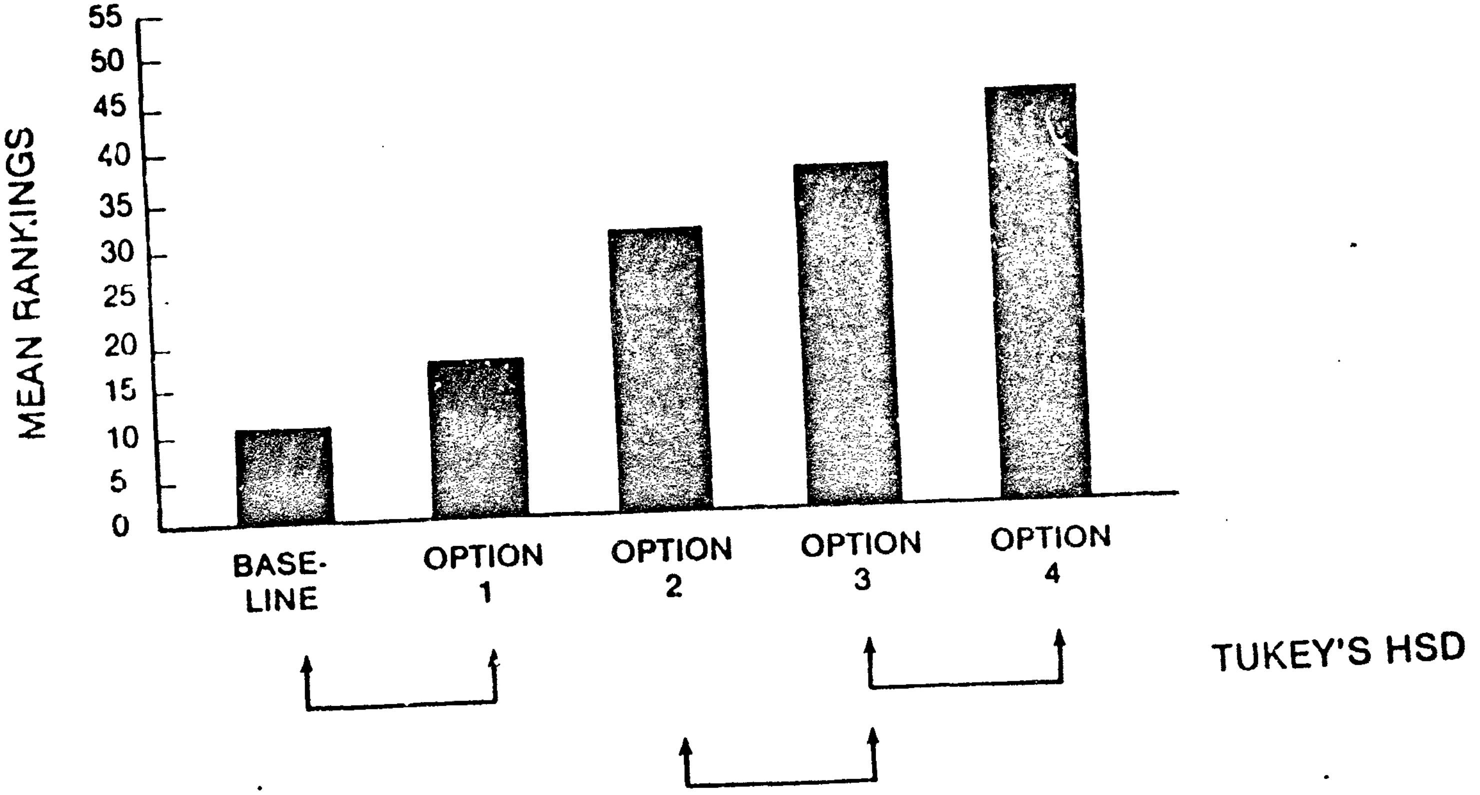

Figure 26. Ranking Data: Pilot Acceptance

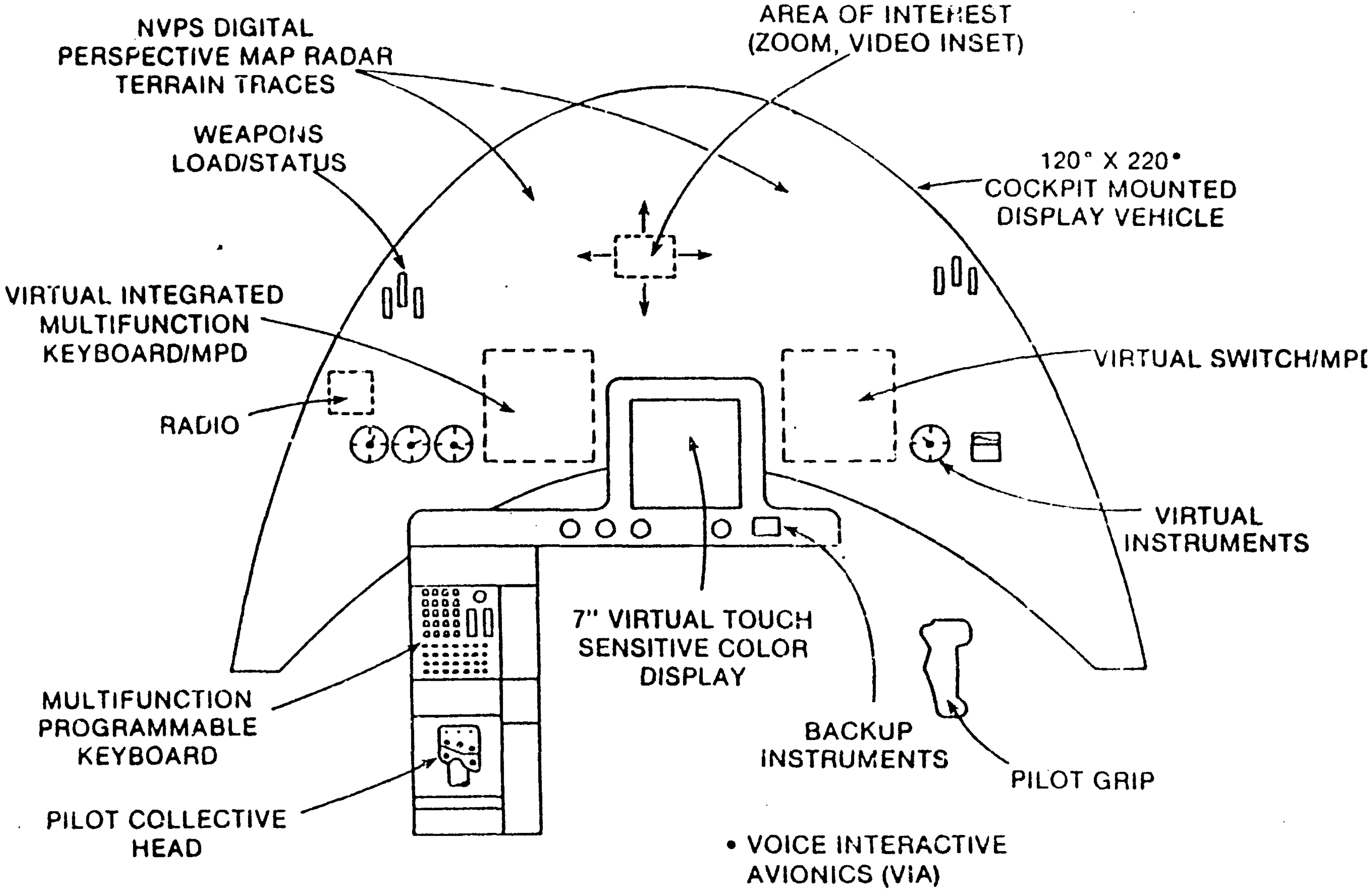

Figure 27. LHX "Ideal" Configuration

Section 7

DISCUSSION AND CONCLUSIONS

DISCUSSION

The intent of this research was to gain early insight into the levels of workload that might reasonably be expected to be found in attempting to conduct LHX/SCAT missions using a weapon system whose crewstation was based on a VPD technology concept. The reader should be aware that numerous factors may detract from the significance of the data reported in this document. The "grains of salt" to be applied are identified below:

a. Time Constraints: The total Technology Assessment Study was accomplished in a 4-month period. A greater duration of the effort might have contributed to a deeper understanding of the issues involved.

b. Subjects: The Ss were assumed to be representative of the pilots who will eventually fly the LHX/SCAT. They may, in fact, be too highly experienced. The Ss were available for participation in the Pro-SWAT and rating scale data collection for only a single day. A longer data collection period might have affected their responses. Only 11 Ss (10 military) participated. A greater number of Ss might have yielded more reliable results although the group appeared to be relatively consistent (Figure 17).

c. MEP: Although AVSCOM participated in the preparation of the MEP portion of the briefing to the Ss and other available references were employed in an attempt to assure the sufficiency and accuracy of the MEP description, this area was still undergoing refinement by the Army during the period of the Technology Assessment Study.' Any differences between the final MEP and that presented to the Ss might have resulted in different responses.

d. Mission Scenario: The mission scenario synthesized by the AFAMRL was based on all available documentation and was reviewed by representatives of the Army Aviation Center. The actual mission asking appropriate to the LHX/SCAT weapon system may differ somewhat from this description which might affect the actual workload levels to be experienced.

e. Pro-SWAT Data: Because of time constraints, all crew system concepts were compared for each mission segment sequentially. This might have been a weakness in methodology and a random order presentation of crew system concept/mission segments might have produced more reliable responses. Secondly, no man-in-the-loop simulation was possible. Simulation might have resulted in the Ss obtaining a better (different) understanding of the concepts (and of the MEP and mission). Simulation is planned, however, during subsequent VPD technology development and validation efforts.

f. "Ideal" Crew System Interface: The five concepts were presented in order of increasing FOV. This may have influenced both the strong expectation for reduced workload with larger FOV options found in the data and, also, might have led to the Ss' apparent expectation that a concept very similar to the panel-mounted projection display system (the last option presented to them) would be an ideal crew system interface.

These several caveats are not intended to suggest that the data are highly suspect. Rather, they should serve as guidance for follow-on experiments to be conducted in extension, refinement, and validation of the present research.

FINDINGS

Pro-SWAT

The predicted workload data suggest two major findings:

a. A wide range i . workload may be expected to be encountered during the conduct of an LHX/SCAT mission (Figures 9 through 15). The exact level of workload that will be experienced may be significantly modified by the crew system interface concept employed by the weapon system. The minimum expected workload level was found for the cruise mission segment, employing Option 4 (cockpit-mounted, wide FOV, projection display), and the maximum expected workload level was encountered for the A/G attack mission segment using the baseline (HUD) crew system VPD.

b. The VPD concepts are predicted to be significantly different from each other in terms of the level of workload to be expected in applying them to LHX/SCAT mission tasks (Figure 9 and Table 4). Over the six mission segments studied, the baseline and Option 1 (narrow FOV, monocular HMD) were never statistically different from each other and always were associated with the highest levels of workload. Options 3 (wide FOV, binocular HMD) and 4 were never statistically different from each other and always were associated with the lowest levels of expected workload. The baseline and Option 1 (as a group) were significantly different from Options 3 and 4 (as a group).

Rankings

Nine qualitative dimensions were examined. In every case, the baseline and Option 1 (as a group) received the poorest score (least desired, made smallest contribution to effectiveness, etc.) and Options 3 and 4 (as a group) received the best score. In all but one case (communications), these two groups were highly significantly different from each other.

a. Situational Awareness: The concepts fell into three groups (Figure 18). The baseline and Option 1 were expected to support situational awareness to the least extent. Option 2 formed a group by itself, between the other two groups. Options 3 and 4 were expected to support situational awareness to the greatest extent.

b. Overall Mission Effectiveness: The groupings were identical to those found for Situational Awareness (Figure 19).

c. Pilotage: Two groups of the VPD concepts were found (Figure 20). The baseline and Options 1 and 2 formed the group expected to least support accomplishment of the pilotage function; Options 2, 3, and 4 for the second group. (The ambiguous presence of Option 2 in both groups means only that it was not felt to be significantly different from any of the four other VPD concepts in its ability to contribute to pilotage.)

d. Navigation: Three groups were found (Figure 21). The baseline and Options 1 and 2 formed a group that was expected to least contribute to task accomplishment. Options 2 and 3 formed a second group. Options 3 and 4 formed a group that was expected to make the greatest contribution to performing navigation tasks.

e. Communications: Three groups were found (Figure 22). The baseline and Options 1 and 2 were least expected to support this function. The baseline and Options 2 and 3 were expected to perform somewhat better. Options 2, 3, and 4 were expected to best support accomplishment of this function.

f. Target Acquisition: Three groups were found (Figure 23). The baseline and Options 1 and 2 were expected to support target acquisition tasks least effectively. Options 2 and 3 were judged to provide somewhat better task effectiveness. Options 3 and 4 were expected to be best able to support this function.

g. Weapon Delivery: The groupings were identical to those found for Target Acquisition (Figure 24).

h. Survivability: Four groups were identified (Figure 25). The baseline and Option 1 were expected to make the least contribution to system survivability. Options 2 and 3 were viewed as the second poorest contributors. Options 3 and 4 were grouped together as making the second greatest contribution, and Options 3 and 4 were expected to make the greatest contribution.

i. Pilot Community Acceptance: Three distinct groupings of the VPD crew system interface concepts were identified (Figure 26). Options 3 and 4 formed the group that was expected to be the most acceptable to the LHX/SCAT pilot community. Options 2 and 3 were, as a group, the second most acceptable. The baseline and Option 1 were rated as being the least desired by the pilot community.

"Ideal" Crew System Interface

The VPD crew system interface designs proposed by the 11 Ss were essentially the same as Option 4. Opportunities were identified for exploiting the very large FOV display as the context into which a wide variety of other information elements/sources could be inset. The result was a "virtual" cockpit in which almost all the displays and MEP controls could be called up on an as-needed basis. The types and arrangement of displayed information subsets could be tailored to meet the needs of the specific mission segment and the preferences of the pilot.

CONCLUSIONS

a. Options 3 and 4 appear to be the best candidates for a VPD-based crew system for a single-pilot, LHX/SCAT aircraft. A significant reduction in workload is to be expected (based on the Pro-SWAT findings) with these concepts versus present practice in cockpit design (the baseline and Option 1).

b. Options 3 and 4 are expected (based on the ratings questionnaires) to make the greatest contributions to achieving and maintaining good situational awareness, supporting mission effectiveness, and providing required functional support (pilotage, navigation, communications, target acquisition, weapon delivery, and system survivability).

c. Options 3 and 4 are expected (based on the questionnaire results) to be the VPD concepts most likely to be accepted in practice by the LHX/SCAT pilot community.

d. Option 4 most closely resembles the crewstation design concept offered by the Ss themselves as representing the "ideal" crew system interface.

e. Option 2 (narrow FOV, binocular HMD) was found to be only slightly less capable than Option 3 in terms of both the projected workload and the opinion rating scale data.

RECOMMENDATION

Options 3 and 4 should be investigated for possible application to the LHX/SCAT weapon system as the VPD-based crew system interface concepts. If funding/schedule permit, Option 2 should also be included in this consideration.

Appendix A

DISPLAY CONFIGURATION QUESTIONNAIRE

R I 99

Subject Name: ______________________

DISPLAY CONFIGURATION QUESTIONNAIRE

1. Situational awareness is the pilot's ability to utilize the displays provided in the cockpit to create an image of his relationship to:

- geographical features (physical features such as land, water, mountains, deserts; political divisions; navigational waypoints; weather systems),
- terrain obstacles (trees, rivers, buildings),
- air and ground threats,
- air and ground targets,
- sister ships, and
- own-ship health and status (weapons, mechanical, flight control)

within the context of the mission he is to perform.

a. Rate the degree to which this display configuration would provide the pilot with situational awareness for performing the LHX-SCAT mission.

Circle the number on the scale below which you feel applies:

1------2------3------4------5------6-----7

would not provide acceptable situational awareness	would provide optimum situational awareness for each phase and every aspect of the LHX-SCAT mission

b. Comments (What motivated your decision to circle the number on the scale above?):

2. LHX-SCAT mission effectiveness will depend upon the success of the pilot to perform pilotage, navigation, communications, target acquisition, weapon delivery, and survivability functions.

a. How do you feel this display configuration would affect overall success/effectiveness of the LHX-SCAT mission if you were the pilot?

Circle the number on the scale below which you feel applies:

1------2------3------4------5------6-----7

display would
prohibit effective,
safe completion of
critical mission
components

display would
enable effective,
safe accomplishment of
each phase and every
aspect of the mission

Comments:

b. If you were the pilot, how well do you think this display configuration would enable you to perform each of the functions within the LHX-SCAT mission?

Circle the number on <u>each</u> scale below which you feel applies:

PILOTING: 1------2------3------4------5------6------7

NAVIGATION: 1------2------3------4------5------6------7

COMMUNICATIONS: 1------2------3------4------5------6------7

TARGET ACQUISITION: 1------2------3------4------5------6------7

WEAPON DELIVERY: 1------2------3------4------5------6------7

SURVIVABILITY: 1------2------3------4------5------6------7

display would prevent me from performing this function for the LHX-SCAT mission	display would enable me to successfully perform this function for the LHX-SCAT mission

Comments:

3. Rate the degree to which you feel the pilot community would find this display acceptable/desirable for performing an LHX-SCAT mission:

Circle the number on the scale below which you feel applies:

1------2------3------4------5------6------7

display concept would be rejected by the pilot community	display concept would be accepted/desired by the pilot community

Comments:

R-I-103

Appendix B

COMMENTS REGARDING RATING ASSIGNMENTS

COMMENTS: SITUATION AWARENESS

Baseline

"The limited FOV of the HUD would require more crosschecking of the cockpit to understand the situation."

"Due to lack of adequate vision, pilot has need to keep his head on a pivot looking outside A/C."

"HUD limits field of view. Pilot dependent upon A/C attitude to see real-world display."

"You have to move the whole A/C to search for obstacles, threats, or anything else. Cannot see to the side."

"Limited visual assistance for night/adverse weather operations. Cockpit complexity-hardware operation. Target ID/acquisition."

"My concern is the flexibility of the HUD to enhance situational awareness."

"The area of attention (i.e., the HUD) does not provide a broad enough scope of the situation."

"Too many information areas requiring division of attention, thus reducing situational awareness."

"Basically provides situational awareness of operational environment, but it is limited."

"The limited FOV, even with snap-look, creates an unnatural feeling of constraint on head movement."

"Perceived transitional problems when going from HUD to CRT to HUD."

Option 1

"This option is similar to the baseline in that it requires inside the cockpit time to become fully aware of the situation."

"Instrumentation requires independent focal plane. No peripheral vision. You have to decidedly look at a system when you should be looking somewhere else. Too many buttons/switches with too many independent systems. System needs to be more integrated with prioritization built in."

"Biggest factor: HMD provides a 'movable' real-world display. Visual intrepretation extremely important."

"Limited FOV. Better field of regard (FOR). You ran into binocular rivalry between HMD display and what is going on in the cockpit with other displays."

"Threat acquisition is better than baseline but still not adequate. Cockpit too complex. Does not lend itself well to battlefield fluidity."

"Situation awareness will be limited because of HMD (monocular). I like the other displays."

"Provides a great deal of information but the pilot has to work for it."

"Configuration is basically the same as the baseline, therefore, too much diversion of attention. However, the ability (freedom) to slew the field of vision display improves the capability."

"Wider field of view with HMD provides better-than-baseline situational awareness, but still limited."

Option 2

"With the binocular FOV and touch sensitive display, the workload has decreased and the pilot can be made more situation aware with less workload on his part."

"Getting better. Everything on one CRT. The only other thing that requires focal attention is engine status."

"Binocular FOV will decrease psychological stresses, enabling me to assimilate more data usefully."

"I feel nothing is gained with binocular FOV. Maybe if I flew it I would change my mind."

"Operation is simpler. Field of view better. Improved target ID/ acquisition capability."

"In comparison to baseline and Option 1, I have better situational awareness although I liked the separate multifunction displays better than the single."

"Great field of view. Less effort on the part of the pilot."

"This configuration moves the pilot's attention more to the outside of the cockpit than the baseline or Option 1. However, it doesn't free him from continuous return to receive updated info."

"Binocular HMD is probably a significant visual improvement. Touch-sensitive color display reduces cockpit workload in obtaining situational awareness."

Option 3

"All functions easier and made available to the pilot in a wider FOV with all necessary info available."

"Field of view greatly enhanced. Necessary switches in two places. Requires focal attention inside aircraft only briefly."

"Better FOV more information to fly by and to search for other targets."

"Operational simplicity, field of view."

"I've lost a multifunction display and although I know that the display will be made elsewhere, I think that the second MFD is neeced for situational awareness."

"Same as Option 2."

"This configuration is the optimal transition to future technologies requiring minimal training and positive (?) transfer from current pilot understanding."

"HMD field of view is much better in this configuration and situational awareness is much improved."

Option 4

"Good FOV and availability of information."

"Everything is there to see without focus of attention. Everything is at arm's reach. No (minimal) looking down."

"It has what a pilot needs to fly. More visual information. Easier to scan moving your eye than moving your head, stop, look, move your head, ..."

"Field of view. Target ID/acquisition capability. Operational simplicity. Apparent pilot workload reduction."

'Information readily available to pilot."

"Although the situational awareness is outside the cockpit, the panorama of information called up at any time diverts the pilot's attention."

"Cockpit-mounted display shown here provides a much better awareness of operational/situational environment."

COMMENTS: MISSION EFFECTIVENESS

Baseline

"This system would provide some advantages over current A/C. However, it is not as integrated' as needed. Would require too much head-in-the- cockpit time."

"Navigation system is the plus to the baseline. Comms easier to handle (can change without releasing collective)."

"This is all based on experience. Even with system limitations, a pilot experienced in the system, who has adapted to system constraints, will perform well."

"The display is hard to point."

"Limited visual inhibits night/weather OPNS."

"On short missions the pilot would be OK but I believe on extended missions (one hour or more) the pilot would become fatigued."

Option 1

"The inside-the-cockpit time would detract from performing your mission."

"Navigation/comm is the plus. Systems have the same problems as baseline."

"Pilots adapt. HMD provides increased capability while actually reducing pilot workload."

"The HMD can work for pilotage and NAV. Target acquisition, weapon delivery, and survivability assume you will have to change magnification and, therefore, do not retain pilotage and navigation.

"Visual system limitations (field of view). Target ID/acquisition."

"OK for short missions."

"Same as baseline."

Option 2

"Less head-in-the cockpit time allows the pilot to concentrate his attention on the situation and mission rather than 'working' to become aware of it. This should result in increased mission effectiveness."

"More time alloted--decrease in work/'look' load."

"A psychologically relaxed guy will perform better (my opinion)."

"... nothing is gained with binocular FOV ..."

"Lends itself better toward reducing pilot workload."

"Improves pilot durability."

Option 3

"Pilot given more time to keep outside. Systems watch themselves. Minimum buttons."

"Better FOV to fly with and navigate, but still ID had-pointed for weapon delivery."

"... second MFD is needed for situation awareness."

Option 4

"The FOV and virtual switching decrease workload, thus allowing the pilot time to concentrate on the immediate mission. Result, increased effectiveness."

"Everything around/in front of you (vision, switches, systems, etc.). Pilot is outside. More survivable. Always acquiring even if he only picks up movement out of the corner of his eye. System (hopefully) automation in acquisition. Pilot only has to react."

"Best option."

"Serious concern on display fixation."

COMMENTS: FUNCTIONAL SUPPORT

Baseline

"TGT ACQ/WPN delivery not timely. HUD monodirectional, without peripheral. Cross-focusing attention between threat, systems, and NAV CRTs/indicators does not allow total system knowledge at a single glance."

"Target acquisition difficult with narrow field of view. Weapon delivery only marginally easier."

"At night you could not see anything except for things in your FOV. I would not like to go out on a multiship mission. There would be a great change of mid-airs such as with the old full face goggles."

"Mission changes could be a problem, i.e., updating navigation information or entering NAV data. Target acquisition in such a limited field of view will be a show stopper."

"The 'piloting' would be degraded because of the constraints on the HUD."

"Would require continuous movement by the pilot."

"Once again, the division of attention in this configuration prevents full task utilization with one pilot."

Option 1

"Need more information simultaneously when required."

"Due to separation of instrumentation, we still have a requirement to focus on too many independent systems."

"Key word would still be adaptability."

"Pilotage--very high workload already. NAV--time to interpret what you are looking at, i.e., FLIR target acquisition--if flying with 1 to 1 (unity) magnification, no better than naked eye. Weapon delivery--inaccuracy of head movement. Survivability--small FOV."

"Still a large workoad for a single cockpit. Not enough help in the visual system."

"... there are constraints on the monocular HMD."

"Navigation and communications information appears ore readily available."

"This configuration is obviously suited to a scat role, whereby those inherent functions are connected to head movement."

"Only improvement over baseline is field of view, but it is an improvement."

Option 2

"The pilot is made aware of the situation easier, thus giving him time to perform these tasks."

"The more time the pilot has to keep his head outside the aircraft (saved by not looking at three different systems, versus two, and pushing buttons), the more acquisition/WPN delivery/survivable you (have)/are (more awareness)."

"Better field of view."

"...Based on the capability of 'seeing' outside the cockpit."

"Pilot appears to have better access to weapons systems and threat info."

"With his attention outside more, the pilot is in a more comfortable psychological state, improving performance.

Option 3

"... due to increased filed of view and time/work/look load decrease."

"Getting better!"

"Greater field of view might improve threat survivability."

"Same as Option 2."

"With the HMD, the pilot is free to move his sights where he wants them. He can accentuate his FOV with optics and minimize his workload."

Option 4

"Better than (AH-)58/Cobra/AAH."

"Pilotage, NAV--sounds and looks like it is day VFR flying at night. Target acquisition, survivability--can detect movement easier ... it is all in your FOV so you can sense movement in your peripheral vision. Weapon delivery--just point better than a gunner."

"Pilots can always get lost. The weapons and threat information will create better awareness on the part of the pilot."

COMMENTS: PILOT ACCEPTANCE

Baseline

"This configuration appears to be only a step in the right direction. Pilots would prefer it over current cockpits, but would want further integration to make the job easier."

"Better than OH-58A/C/D AHIP with reference to NAV, COMM, etc. However, confusing with reference to 'where to look' to get 'what information'."

"Compared to the other options, this is the least desirable, Of course, the SCAT community would adapt it to optimize performance."

"Target acquisition limitations create a problem in the attack role."

"It would be accepted as is if placed in the aircraft. But when a better system evolved, all pilots would ask for the better system."

"Would be an improvement over anything currently in use."

"It is better than nothing, which we have now, but could be easily improved."

"Although this is the 'here and now' state of the art, it is limited in its use for some LHX-type missions."

Option 1

"... better than current systems but still stops short of what is needed to be successful in a one man LHX."

"Better than OH-58/A/C/D and AHIP."

"Preferable in some cases to what we have now. FLIR is question mark in my mind."

"From experiences in PNVS, would it be compatible with glasses?"

"Coping with battlefield changes might create a dangerous distraction. 'Cover me while I reprogram the system' might become a common phrase."

"The helmet mounted display might require extensive training, initially for pilot acceptance since it is a major change from current operation. It would probably be gradually accepted, however."

"Would improve mission success."

"The present community is comfortable with this configuration only because it is familiar."

"Better than baseline configuration for field of view, but still limited."

Option 2

"Less head-in-the-cockpit time allows the pilot to concentrate his attention on the situation and mission rather than 'working' to become aware of it. This should result in increased mission effectiveness."

"More time alloted--decrease in work/'look' load."

"A psychologically relaxed guy will perform better (my opinion)."

"... nothing is gained with binocular FOV."

"Lends itself better toward reducing pilot workload."

"Improves pilot durability."

"Better than OH-58 series and Cobra."

"Increased capability, slightly reduced workload."

"This option would be more readily accepted than Option 1."

"More information to pilots."

"This configuration reaches the limits of current understanding and, therefore, would require some initial use for acceptance."

Option 3

"All necessary information is made available to the pilot in a wide FOV allowing him to have a larger situation awareness window with information when needed."

"Better than [OH-]58/Cobra; same as AAH."

"Virtual keyborad is far out feature!"

"More info/less effort on the part of the pilot."

"Although this is the optimum, there would be increased training required."

Option 4

"In my opinion, similar to Option 3. Either option would be accepted by the pilots as acceptable."

"Same general comments as for Option 3."

"Where are backup instruments?"

"I feel that nis option would probably suit me best. Actually in such a cockpit may cause me to reconsider."

"The new pilots are from the Star Wars and Tron generation and will accept the technology."

"Once again any information called to the display diverts the pilot's attention. Whereas, if he knew to look in one spot (Option 3) his attention is controlled."

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ANNEX R-II

HUMAN FACTORS ENGINEERING REVIEW OF THE INTEGRATED CREWSTATION FOR THE LIGHT HELICOPTER FAMILY (LHX)

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Annex R-II to Appendix R

HUMAN FACTORS ENGINEERING REVIEW OF THE INTEGRATED CREWSTATION FOR THE LIGHT HELICOPTER FAMILY (LHX)

R-II-1. The report, "Human Factors Engineering Review of the Integrated Crewstation for the Light Helicopter Family (LHX)" is reproduced on the following pages. The report was prepared by Richard N. Armstrong of the Human Engineering Laboratory, Fort Rucker, AL.

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HUMAN FACTORS ENGINEERING REVIEW OF THE INTEGRATED CREWSTATION FOR THE LIGHT HELICOPTER FAMILY (LHX)

Prepared by:

Richard N. Armstrong

U.S. Army Human Engineering Laboratory

11 May 1985

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HUMAN FACTORS ENGINEERING REVIEW OF THE INTEGRATED CREWSTATION FOR THE LIGHT HELICOPTER FAMILY (LHX)

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HUMAN FACTORS ENGINEERING REVIEW OF THE INTEGRATED CREWSTATION FOR THE LIGHT HELICOPTER FAMILY (LHX)

1. OVERVIEW.

The combat effectiveness of the light helicopter family (LHX) largely depends on the aircrew's ability to successfully operate the aircraft and its onboard equipment and systems in flight. To obtain the best overall operational effectiveness, the interface between the aircrew and aircraft must be designed to effectively capitalize on the capabilities of technology and the aircrew.

Early crewstation's designs were relatively uncluttered and contained only minimal instrumentation, displays, controls, and flight systems necessary for optimal daylight flying. These systems were well within the capabilities and workload limitations of the aircrews. As the full potential of Army aircraft was realized, mission requirements and aircraft crewstation configurations began to change. New dedicated devices and systems were added, each competing for the limited space within the field of view (FOV) and reach of the aviator. Each new function or system added normally resulted in the addition of one or more dedicated displays or controls. Due to the limited space within the crewstation, it was not always possible to place the new controls or displays in a position that maximized human effectiveness.

The additional workload imposed by the large variety of systems incorporated into the crewstations was further complicated by more demanding missions. When the primary Army aviation mission was combat support, transporting soldiers and equipment at relatively high altitudes, aviators were afforded more than sufficient time to cross-check instruments, tune radios, monitor their crewstation systems, and fly the aircraft. With the addition of close combat missions and the advent of highly sophisticated ground-to-air weapons deployed by the enemy, Army aviation was required to change tactics. The luxury of flying well above the terrain is no longer affordable. Helicopters are now required to utilize terrain flight techniques, often flying below treetop levels to avoid enemy detection. When flying in the terrain flight regime, most of the aviator's attention must be concentrated outside the aircraft, leaving little time for monitoring instruments or for operating controls and systems inside the crewstation.

The requirement to be able to fly and fight around-the-clock further compounds the problem. When flying at night or at reduced visibility levels, the aviator's capability to see things outside the aircraft is greatly reduced. To ease the burden of flight at night, new technologies like image intensification night vision goggles (NVG), low-light level video cameras (LLTV), and infrared (IR) video systems have been incorporated into Army helicopters. These systems do provide an enhanced night flight capability, but they have increased the number of displays and controls the aviators of dual-crew aircraft must be attentive to, thereby increasing the aircrew workload.

The increased demands of future conflicts, coupled with the addition of new and more complex systems in the crewstation, could easily reach a point where, if not properly integrated, the crew workload or attention level may prevent obtaining the maximum effectiveness from the aircrew and aircraft in the highly intense and dynamic conflicts of the future.

Technological advances over the past years have demonstrated a considerable increase in the capability of aviation systems and mission equipment. Human or aircrew capabilities, on the other hand, have increased in the domain of knowledge and training, but the aircrew's cognitive and sensory capabilities, anthropometry, and environmental requirements have changed very little. For example, the capability to present visual information on displays in the cockpit has changed from the dedicated dial and moving needle to graphically presenting information on electronic displays. The aviator's visual capabilities and limitations, on the other hand, remain essentially the same as they were in the past. To assure the success of the LHX in future conflicts, aircrew workload must not be allowed to exceed a level that restricts the effective use of the full aircraft capabilities.

Applying advanced technology is certainly an appropriate way to improve performance and overcome the space and weight limitations in modern aircraft, as long as its use remains within the abilities and capabilities of aircrew that must operate the system. The change from current crewstation configurations to a more sophisticated design is expected to shift the crew workload from one that is manual or physical to one that is more demanding from a cognitive and mental workload aspect. In effect, the aviator whose role in the past was one of system operator and information integrator becomes one of a system manager.

Electronic and avionics systems may be available in the LHX development time period that can gather and provide all the information needed to fight and win future conflicts. The information can, however, only be useful if presented to the aircrew at a rate they can assimilate and effectively use. To best optimize available technology, it is vital that the aircrew be provided essential flight and mission information in a way that allows them to become an integral part of the system. The operation of advanced Army combat aircraft demands that information be organized and presented so that the aircrew will be provided with preprocessed data relevant to the specific mission or flight phase they are engaged in.

The challenge in the LHX is to maximize system performance through the appropriate assignment of mission functions to the aircrew and the aircraft in a way that uses the best attributes of both man and machine. The crewstation displays and controls, with which the aircrew interact, must be designed to capitalize on the crew's capabilities. One of the goals of the LHX program is to design an aircraft that is mission effective with a single crewmember. To accomplish that goal, the functions now performed by the second crewmember in current aircraft must be automated or transfered to the single crewmember.

Flying low levels and NOE below treetop levels is extremely demanding on the flight crew. NOE flight requires the pilot to focus most of his visual attention outside the crewstation while rapidly maneuvering the aircraft around obstacles in the flight path. Add the other crew tasks like navigating, communicating, target acquisition and engagement and monitoring of the aircraft subsystems, and the demand on the aircrew's physical and mental abilities rapidly increases. The requirement to fly and fight around-the-clock further compounds the problem.

The increasingly hostile environment Army aviators must fight in and the number and complexity of new aviation systems requires a large amount of information be presented to and assimilated by the aircrew. The most essential ingredient of the design of the LHX for the future battlefield is the integration of the vast amount of information provided by the aircraft sensors into a form that can easily be interpreted and used by the aircrew.

The goal of a single-crewmember LHX demands an even more efficient crewstation design. The full integration of the information displays, the control techniques employed, and the capabilities and limitations of the aircrew at a level much greater than current aircraft is mandatory, if that goal is to be achieved. The functions the aircrew must perform in the LHX fall into the major functional areas of flight control, navigation, communication, target acquisition and engagement, survivability, and system status monitoring.

Each of these functions is of prime importance when the LHX enters combat. The inability of the aircrew to effectively perform any one of these functions could result in degraded performance and loss of mission success.

A review of the crewstation integration of recently developed aircraft supports that hypothesis. Both the AH-64 attack helicopter and the OH-58D scout helicopter requires a crew of two to peform their missions even though some of the technology and crewstation integration proposed for the LHX can be found in those helicopters.

In a single-crew LHX, many of the crew duties must be automated to take up the slack left by the second crewmember. That automation must be extensive and flexible enough to provide the crew the option to use whatever automation is best suited for the particular mission they are involved in at a specific time.

A review of the major human factors engineering issues of the LHX crewstation integration concerns has indicated that the capabilities and limitations of the human must receive additional consideration. The LHX is expected to be a highly automated helicopter with the capability to provide the aircrew with a continuous flow of essential information. It is the integration of that information into the crewstation, along with the processing of that information by the crewmembers and the resulting control actions on the part of the aircraft that require much attention from the human factors engineering viewpoint. Traditionally, the system design phase, making the hardware work, has consumed most of the allotted time scheduled for development of a new aircraft. If the LHX is to truly provide the effective combat system needed to meet the future threat, the human factors engineering effort must be given as equal an emphasis as the hardware operational design. The human factors engineering analyses presented in the AVSCOM TOD and this TRADOC TOA, along with the preliminary results provided thus far from the ARTI program, all contribute to the assessment of the soldier-machine interface of the LHX and the enhancement of the crew's operational capabilities and the manpower, personnel, and training requirements. These preliminary efforts provide a framework for the development of the LHX but do not answer all the human factors engineering related issues. Human factors engineering for the LHX crewstation is part of an *iterative* design process that must be continually reviewed and updated. The operational success of the LHX on the battlefield is dependent on that process continuing.

The remainder of this paper will address various aspects of the LHX crewstation and examine some of the crew functions for which new technology may positively impact. Workload is considered in light of the time spent on specific crew activities or the attention aviators must devote to any specific aircraft function. The major areas considered include: navigation; communications; flight controls; subsystem monitoring; target acquisition/designation; survivability systems; nuclear, biological, and chemical (NBC) protection; life support equipment; and controls and displays. Each of those areas are discussed separately, but in the final LHX configuration, it is essential that they be fully integrated to provide minimal workload for the aircrew. The major sources of information considered in this analysis included the Army Aviation Mission Area Analysis (AAMAA), the LHX Trade-Off Determination (TOD), and the individual reports submitted for inclusion in the U.S. Army Aviation Center's (USAAVNC) Trade-Off Analysis (TOA). It is assumed that the detail design of the airframe, crewstation, and the controls and displays will incorporate all human engineering principles and data regarding the physiological and mental capabilities and limitations of the air and ground crews expected to operate, maintain, and rearm and refuel the LHX.

2. NAVIGATION.

The success of the LHX in future conflicts will depend primarily on the ability of the aircrew to maneuver their aircraft to the right place at the right time. That ability, in turn, depends on being able to successfully perform the task of navigation. In that regard, navigation encompasses not only movement from one point on the battlefield to another but the ability to accurately accumulate, record, use, and transmit position information concerning the threat and friendly forces. Mission success also requires the crew to maintain an overall situation awareness of the rapidly changing tactical situation around them.

Studies and evaluations of the relationship between human performance and currently fielded navigation systems reveal that they yield performance less than that needed for the LHX. This less-than-desired performance is due, in part, to a number of factors including loss of perspective, map design, navigation sensor accuracy, and display designs. Evaluations of more recently developed and available navigation systems indicate those systems do much to enhance the present capabilities to navigate and maintain a situational awareness of the battlefield, but further improvements are needed if the maximum effectiveness of the LHX capabilities is to be realized.

Projected map displays (PMD) utilizing remote map reader technology that take map information stored on film and project it onto a multifunction display, improve current systems by taking the traditional map information out of the aviators lap and placing it on a display in the instrument panel of the aircraft. In tests conducted so far, an aircrew of two, when using a projected map, can navigate terrain more rapidly with fewer delays and course disorientation and less visual attention devoted to the navigation task than previous navigation systems. The copilot/navigator does, however, still devote about one-fourth of his total visual attention to the navigation system. In addition, the navigation system requires manual updating every 10 to 15 minutes of flight.

Digital map technology, because of its inherent flexibility, provides a greater potential for mission success in the LHX. The digital map approach uses as its source of information geographic data produced by the Defense Mapping Agency in a digital form that can be stored in the memory of flight computers. During flight, these data are converted back into a display that can be used by the aircrew. The digital map technology not only has the potential to provide a horizontal display much like the projected map display, but when fully developed, it could provide a vertical display as well. Another advantage of the digital map system is the capability for the aircrew to select the type and amount of information to be displayed. Because of their common tri-service use by both ground and air forces, current paper maps and projected map displays often contain more information than can be used by Army aviators. With the digitally generated data base only the information that the aviator chooses is presented on the crewstation display. In a sense, the digital map display can be decluttered. The digital map system also has the potential to automatically calculate and display the optimal flight path the aircraft can follow to best avoid the known threats. The exact level of visual attention and crew workload required by the digital map system has not yet been determined. The available systems are still in the simulation evaluation stage. It is speculated that the visual attention will be less than that of the PMD, but it could still be relatively high. If the visual attention and crew workload associated with the panel-mounted digital navigation system approaches that of the panel-mounted display (PMD), additional display techniques will be necessary to enhance the LHX performance, specifically in a single-crew LHX. While flying missions at terrain flight levels, the single crewmember should devote as much visual time outside the crewstation as possible. He can ill afford to spend one-fourth of his attention on the navigation task. Navigation information should, therefore, be provided to the aviator in a manner that allow him to keep his eyes outside the crewstation during terrain flight. Simulation and flight tests to specifically address the most effective means of providing navigation information to the aircrew, when their attention is focused outside, will be necessary if maximum effectiveness of the LHX is to be obtained.

The digital map data base also has the potential to provide inputs into an automatic terrain following and avoidance system. With such a system, the pilot could be relieved of much of the workload associated with the task of flying. That technology, unfortunately, has not yet matured. The current digital data base, with around 100-meter (m) accuracy, along with sensors to detect small objects like buildings, trees, and wires require considerable improvement if full terrain following and avoidance are to be achieved.

The LHX navigation system review indicates that, at a minimum, a horizontal situation map-like display should be provided that gives the aircrew real-time accurate, spatial information concerning their aircraft position and the position of friendly and threat forces during day, night, and adverse weather conditions. In addition, the system should allow the aircrew to rapidly obtain information from the display with minimal head downtime inside the crewstation, provide a means to automatically update the position information, allow the user to annotate the display with friendly and threat information, and provide the capability to rapidly transfer information to other members of the combined arms team. The need to develop methods and techniques to allow the aviator to keep his attention focused outside the aircraft while navigating is of particular importance to the single-crew aircraft where the copilot is no longer available to attend to the navigators task. From a human factors engineering perspective, the potential of the digital-based navigation system appears to provide the better choice for the LHX, assuming the systems currently under development are sufficiently mature by the full-scale development phase of the LHX. If the goal for a single-crew LHX is to be accomplished, a high priority must be placed on the improvement of navigation sensor accuracy, the availability and accuracy of digital data base information, and improved methods for displaying navigation information to the aircrew.

Any candidate navigation system for the LHX should be considered in terms of the system workload demand. Navigation systems typically demand to be fed information during system start-up and alignment, flight planning, sensor updaing, and en route waypoint entry. Currently fielded systems require from 5 to 20 minutes to load data through a keyboard during the pre-takeoff phase of the mission. Updating the navigation system accuracy is required on a frequent basis during the mission and the crew must spend valuable time telling the navigation system its present position so that it can then tell the crew their present position for the next few minutes. Data loading should be able to be accomplished in the aircraft without using a keyboard and should not require more than a few minutes. System updating should be required infrequently and easily accomplished. The navigation system should support the pilot in the performance of his mission, and minimize the demand on his time and attention.

3. NUCLEAR, BIOLOGICAL, AND CHEMICAL (NBC) DEFENSE.

Army aviation can expect to encounter NBC threat weapons during future conflicts. The Soviet Union and Soviet-backed forces have the capability of employing a vast array of such weapons and the capability to protect their own troops during such an attack. The LHX must incorporate design features that can successfully counter that threat. Analyses of NBC defensive measures have highlighted three basic approaches that can be used to protect the aircrew from the threat: contamination avoidance, collective protection, and individual protection.

The most effective means to prevent casualties and protect the aircraft from the NBC threat is perhaps avoiding the threat completely. Although contamination avoidance may not be used in all cases, it is an available tactical measure for the commander in the field when the situation permits. The option of contamination avoidance will only be successful if aviation units are provided a reliable means to determine if an attack is imminent or has occurred. The ideal situation would be the identification of contaminated areas at some standoff distance from the aircraft. Remote standoff detection devices are required for the LHX to fully exercise the option of contamination avoidance. Detectors in the inventory are of the point sampling type normally used on the ground. As such, they must be placed in the contaminated area to detect the contamination. Preliminary flight testing has indicated that it is possible to modify some of those systems for flight use. Standoff detectors, on the other hand, are in the early development phase. If a standoff detection capability is to be achievable for the initial fielding of the LHX, those programs need to be given a priority equal to the LHX program. Contamination avoidance is a tactical measure that can be advantageously used when the combat situation permits but it does not provide a complete solution to the NBC threat.

Collective protection provided to the aircrew by way of an LHX that is completely sealed and pressurized, to prevent contaminated agents from entering the aircraft, would also provide a considerable tactical advantage. Collective protection would allow personnel to operate in normal flight clothing, thereby, overcoming the performance decrements imposed by protective clothing. In addition, collective protection would also protect the aircraft avionics, aircraft materials, and other equipment or systems inside the aircraft from destructive agents. The need for decontamination of the interior of the aircraft would also be reduced. Collective protection, however, cannot assure total survival of the LHX on the battlefield. Full protection could be lost in the event of damage by enemy fire that breaks the integrity of the sealed aircraft, or when it is necessary for the aircrew or passengers to enter or exit the aircraft in a contaminated area. Collective protection alone is not the solution.

Current protective clothing that encapsulates the individual in an NBC protective suit and mask provides a life-saving capability, while allowing the individual to continue to operate on the battlefield but at a considerably reduced level of effectiveness. The protective clothing and masks introduce problems associated with degraded crew performance like heat stress in hot climates, restricted aviator movements, a lack of manual dexterity and sensitivity of touch, a restricted FOV, reduced visual capabilities, increased aviator workload, and fatigue. All these factors combine to create a large decrement in crew performance. Individual protection much like collective protection and contamination avoidance allows the aircrew to continue the battle but by itself is not the optimal way to meet the NBC threat.

The most viable solution for the LHX appears to be a hybrid collective protection system that maximizes the advantages of all three approaches: contamination avoidance, collective protection, and individual protection. Such a system could allow the aircrew to operate in a pressurized aircraft, partially clothed in NBC gear under normal or routine conditions. The contaminated area could be avoided when onboard detectors warn of its existence ahead of time and the battle conditions allow the commander to exercise this option. When approaching a known contaminated area or when the aircraft detectors indicate the aircraft is in a contaminated area, the full NBC protective measures could be taken. This approach would allow for maximum crew effectiveness to be obtained when not in a contaminated area, as well as assure protection to the aircrew when in a contaminated area. The technology to do this appears to be available well within the LHX development time frame.

To take full advantage of this concept, NBC agent detectors should be located both inside and outside the aircraft. The aircrew would then be able to determine when they are in a contaminated area and whether the contamination has penetrated the crewstation. A remote standoff detection capability should be added, when available, to avoid the contamination completely. A sufficient cooling capability must also be incorporated into the crewstation to prevent aviator heat stress in hot environments. The use of aircraft environmental control systems in conjunction with microclimate cooling vests worn by the aviator appears to meet this need.

In addition to the hybrid system and cooling provisions, the crewstation configuration and the design of the controls and displays should provide adequate room and space for the aviators to operate the LHX when fully dressed in NBC clothing and other life support equipment.

4. FLIGHT CONTROL.

The helicopter is basically an unstable, vibrating platform suspended in space by a spinning rotor blade. The task of the aviators when flying such a system is twofold. First, the aviators must fly the aircraft from one location to another and secondly, they must maneuver the helicopter into a position so that they can effectively complete their combat mission and defeat the enemy. To accomplish that task, the helicopter itself must be extremely agile and maneuverable. The flight controls of current Army helicopters consist of three separate control levers that control mechanical systems with hydraulic boost. Two of the control levers require manipulation by the aviator's hands while the third is moved by the aviator's feet. A review of the evaluations concerning manual control and workload suggests that even under the most favorable conditions, a large percentage of the pilot's attention is required for manual control of the helicopter. That effort is particularly demanding during mission conditions involving poor visibility, variable winds, and terrain flight where the aircrew is continuously maneuvering around trees and obstacles. At a minimum, the LHX should provide some level of automatic control and stability augmentation to assist the aviator and reduce the amount of attention, control movement requirements, and workload imposed on the aircrew. The less attention the pilot must devote to the task of controlling the aircraft, the more time he will have to perform other operational functions, thus enhancing the probability of mission accomplishment. This is specifically important during terrain flight where the fatigue factor is 1.3 times higher than during normal flight.

Another aspect of crew workload associated with flight controls is the physical interface between those controls and the human operator. Aviators in today's Army come in all sizes and shapes. It is difficult to design a crewstation that will properly accommodate all of these. If the crewstation is not optimally designed, the adverse effects on the human will degrade operator performance. Investigations directed toward the evaluation of aircrew anthropometeric dimensions and crewstation configurations have pointed out that in current helicopters the crewstation internal space in combination with the fixed cyclic control position does have an adverse effect on the aviator. To reach the cyclic control grip, while simultaneously resting their arm on their leg, a number of aviators are required to assume an exaggerated forward "slouched" position. That position places a curvature in the human spine that is susceptible to vibrational stress and fatigue during normal flight resulting in back problems for the aviator. The "slouched" position also increases the probability of back injury during a crash. In addition, the forward "slouch" position tends to restrict the aviator's forward vision outside the aircraft and shift his eye position away from the optimal design eye position used for reference when determining the placement of controls and displays in the crewstation.

Aircrew protective gear and life support equipment also creates an interface problem with current aircraft controls. Larger aviators, wearing full NBC gear and body armor often restrict the full movement of aircraft controls. The situation can be partially relieved through a better seat and aircraft control position relationship. Improved adjustments on both the seat and the control levers in both the horizontal and vertical planes would be one way to reduce the need for the aviators to "slouch" when flying.

A second solution would be to remove the position constraints imposed on the aviator with current type aircraft controls (cyclic, collective, pedals) by replacing them with a single "side-arm controller" that could be operated with one hand. One such system, the advanced digital/optical control system (ADOCS), is undergoing development. From a human factors perspective, the "side-arm controller" has a number of advantages. First of all, the aviators should no longer need to "slouch" forward in the crew seat to reach the flight controls. Secondly, the aircrew should be afforded more freedom to position their bodies in a more comfortable position in the aircraft. Thirdly, the relocation of the cyclic control function from in front of the aviator would remove one of the visual restrictions between the aviator and his instrument panel. The relocation of the collective control head would also remove the visual restriction between the pilot and the avionics control panels in the center console. The increased unrestricted FOV not only enhances the aircrew's capabilities but allows the crewstation designer more freedom in which to place displays in the crewstation.

From a handling qualities point of view, the use of fly-by-light and likewise fly-by-wire concepts should afford more flexibility to design the aircraft control system in such a manner that aviator workload and attention devoted to the flying task is reduced. With such a system, control gains and transfer functions could be tailored to provide the best controllability for various maneuvers. Such tailoring could be selected by the pilot or perhaps automatically by sensing appropriate aircraft state variables or operator inputs. It would also provide an avenue whereby information from other aircraft system sensors could be inserted into the control loop for increased automation of the flight control function.

Flight control and maneuvering of the aircraft is an attention-consuming task for the pilot during flight when well above the terrain. Terrain flight, down among the trees and obstacles is much more demanding. Based on studies of current helicopters, the pilot of a two-crew aircraft must devote most of his attention to the flight control tasks, leaving other tasks like navigation and communications to the copilot.

With expanded missions and advanced capabilities expected in the LHX, it would be advantageous to the overall success of the mission if the pilot of the aircraft could spend less attention on the flight control task and more attention on other combat functions. From the human factors point of view, it appears to be a minimum requirement, when considering a single-crew LHX. From the limited testing conducted so far, the evidence indicates the fly-by-light and/or the fly-by-wire concept of flight control has the potential to relieve the pilot from some of the flight control effort. That potential, for improved handling qualities, automatic stabilization, and flight of the aircraft, should be pursued. The use of a side-arm controller to replace the three separate controls now found in helicopters also has some advantages with respect to the reduction of stress and fatigue caused by the aviator's "slouched" position, the removal of visual restrictions between the aviator and the controls and displays, and the increased flexibility afforded the crewstation designer regarding the placement of displays. In addition, the integration of the control functions into less than three separate controllers should relieve the pilot from having both hands and feet simultaneously occupied in flying the aircraft. The question concerning how many of the three control functions should be placed on a single side-arm controller remains unanswered. Although the aviator's physical workload may be less under the side-arm controller concept, the cognitive and mental workload associated with that task may very well be increased. Additional investigation through simulation and flight testing are needed to address that concern.

5. SYSTEM STATUS MONITORING.

The monitoring of the health and status of various aircraft systems (engine, transmission, electrical system, hydraulics, fuel flow) are considered to be an essential task to assure safe flight. In today's aircraft that information is displayed in the crewstation, on the instrument panel and center console, through the use of as many as 14 round dials and gauges, for quantitative information, supplemented by over 20 discrete lights and audio tones.

Quantitative information is displayed when the conditions involved are dynamic and require continuous monitoring. Examples of this type of information would include the amount of fuel left in the aircraft fuel tanks, engine pressures or temperatures, and electrical system voltage levels.

Continuously displayed quantitative data provide the aviator with trend information concerning the parameters monitored. Trend information is important to the aircrew because it permits them to assess the overall system status, detect impending adverse conditions, evaluate how rapidly the adverse condition is progressing, and take action to stop or reverse the trend.

Discrete information displays are the type that provide binary information that indicate if the state of the system monitored is either good or bad. The master caution light is a good example of that type of display. When the light is not on, it indicates the systems monitored are operating within a "safe" condition. When the light is on, it indicates a problem that requires the aviator's attention. It does not provide quantitative or trend information.

Both the quantitative and discrete displays convey needed information but there is some concern as to how well that information is detected and used by the aircrew. Several studies have shown that during terrain flight, the attention of each member of a two-man aircrew is virtually consumed by the tasks of flight control, terrain and obstacle avoidance, and navigation. Less than 10 percent of their time was devoted to monitoring other flight instruments, communications controls, and system status displays. Add to this the task of observing enemy movements, target detection, and combat communications, the time available for monitoring system status displays will be further decreased. Flying at night will also compound the problem. During the heat of battle, the aircrew cannot afford the time required to monitor the aircraft system status, but on the other hand, if that task is not accomplished, it could lead to disastrous results.

The timely acquisition of both quanitative and discrete system status information and the decisions based on that information is important to the LHX survivability. How well that is accomplished is dependent on the information being available and the aircrew having sufficient time to monitor the displays to obtain the information quickly. This presents a considerable challenge in a two-crew aircraft, where one crewmember may be able to devote some of his time to monitoring the system status. In a single-crew LHX, the need to relieve the aviator of this task is more critical.

The data related to the status or condition of aircraft subsystems are demand-type information. Aviators require that type of information to assure them that the aircraft systems are operating properly and to warn of a possible impending failure. Under normal operating conditions, some status information is not necessarily needed except to build the aviator's confidence. The demand for system status information becomes critical when the systems being monitored are not operating well and could result in degrading of the mission or losing the aircraft.

Considering the limited time available for system status monitoring and the type instruments used in most fielded aircraft, it is very probable that the aircrew may not detect a rapidly developing out-of-tolerance condition when flying nap-of-the-earth (NOE). First of all, NOE flying requires that most of the crews' attention be focused outside the cockpit. Secondly, humans by nature, are not good monitors of relatively slow-changing displayed information. Aviator's tend to rapidly scan such displays but do not always obtain the necessary information from them. During a 5-day aviator fatigue study in a UH-1 simulator, it took the flight crew from a few seconds to 20 minutes to notice the engine oil temperature had reached a point well above the red line. Another aspect of the problem with system-monitoring displays is the large amount of panel space required for those devices. The system-monitoring displays occupy a disproportionate amount of panel space compared to the amount of time the pilot views these displays.

The ideal aircraft system status monitoring system should be one that is capable of sensing a changing trend in system status, determining if that trend is within or approaching tolerance limits, and then warning the crewmembers when the system status is approaching an adverse condition that requires their attention. The aircrew can then assess the problem and implement corrective procedures when needed. From a human factors engineering perspective, system status monitoring is a prime candidate for automation. Monitoring is a task that humans do not do well, while computers can perform that task extremely well.

The concept of system status management by exception is quite appropriate for the LHX. A computerized monitoring system could maintain constant vigilance, perform trend analysis, diagnose abnormalities, and provide the aviator with the information he requires or desires. If the systems are functioning within tolerance limits, the aircrew need not be provided any information unless they specifically ask for it. When a condition demanding the aviator's attention arises, critical information the aircrew needs for that particular situation could be provided on the crewstation displays.

A concern from the human factors engineering standpoint is the implementation of the concept. In order for the management by exception system status monitoring system to be successful on the battlefield, much attention must be devoted to determining what needs to be monitored, the tolerance limits of the various systems to be monitored, the level or depth to which the computer should diagnose the data received, and when and how to display the information to the aircrew. The recommendation for the LHX is to incorporate the management by exception systems status monitoring concept into that aircraft. Prior to incorporating such a system, specific tests and evaluations should be conducted to answer the concerns above and to assure the concept will, in fact, reduce crewstation workload.

6. COMMUNICATION.

Effective and accurate communications are also critical to the successful completion of LHX combat missions. This is especially true for the scout/attack (SCAT) version. The LHX crew must be able to effectively communicate with a large number of friendly forces. The Army 21 concept dictates a greater need for improved communications with an increasing number of other members of the combined arms team than did past conflicts. To meet this need, additional radios have been placed in aircraft crewstations. Each new addition increases the crewstation workload by increasing the number of controls and displays the aircrew must operate and monitor.

The impact that the addition of individually dedicated radio control display heads has on the aircraft cockpit is best described by the results of the "Advanced Scout Helicopter Man-Machine Interface (MMI) Investigation." That evaluation consisted of a review of the literature supplemented by studies conducted in a crewstation mockup using standard communications systems. The results of that evaluation suggest that 56 percent of the aircrew mission time involves some type of communications distributed across a variety of radios. If the LHX aviators are to be effective on the modern battlefield, the overall time devoted to communications needs to be reduced.

One method of reducing the workload associated with the communications task is to integrate the various radio controls into one panel. Such an integrated avionics control system (IACS) was developed through the Army Avionics Research and Development Activity. A similar system is utilized in the OH-58D helicopter. In these systems, the aviator uses an alphanumeric data entry keyboard along with various switches to select a number of radio functions displayed on an electronic display. These include selection of the type of radio and the specific frequency desired. In addition, the system can be used to control aircraft navigation equipment.

Evaluations of the IACS indicate that the time required to access a specific radio frequency (RF) when using preset frequencies was 13 percent less than with standard control heads. When used in the manual mode, the IACS was no more advantageous with respect to crew workload than the conventional method. The integrated system does, however, provide a definite reduction in the crewstation space occupied by radio control heads and concentrates the display information in a central location.

The evaluations conducted so far with the OH-58D indicate the control of the communications system through a multifunction keyboard is advantageous but that approach will require additional improvements if it is to be a viable option for the LHX single-crew aircraft. For example, the system requires considerable time to manually load initial data into the system during preflight. During flight, the communication task requires progressing through a number of computer displayed pages to communicate and send target information to other aircraft and the ground. In a two-man aircraft, the second crewmember can help with this task but in a single-crew LHX, a less workload intensive system will be a necessity.

Another important factor related to the efficiency of communicating between aircraft and with ground forces is the communications electronics operation instructions (CEOI). The CEOI are classified documents that provide the aircrew with a complete listing of frequencies, call signs, and other critical communications data concerning friendly forces within their operational area. The CEOI are updated every 24 hours with more frequent changes if the system is suspected of being compromised by enemy action. The CEOI are rather large and bulky documents. Aviators must thumb through many pages of the document to find the specific frequency and call signs assigned to the unit they wish to contact. The use of CEOI can consume as much of the communications task time as the tuning of the radios. One method of reducing the workload associated with CEOI, as well as the entry of other communications and navigation information into the LHX, during preflight, would be the provision of a bulk-loading device similar to an audio tape or disk that could transfer pretaped data into the LHX system computers within a few minutes.

Still another communications human factors area that must be considered for the LHX is speech intelligibility. Some of the information communicated by voice in today's aircraft is lost in the noise levels found within the communications equipment itself. Failure to transmit or the need to repeat information that one is trying to communicate easily results in a loss of information or delays that could have an adverse impact on the battle.

The LHX communications systems must provide a less noisy environment and greater speech intelligibility in the overall communications system. The technologies available for incorporation into the LHX appear to be capable of accomplishing that goal. The use of improved sound canceling microhones, more acoustially-efficient earcups, and control system noise suppression techniques would do much to improve the situation.

Another aspect of communications workload that requires attention is the transfer of targeting information to other aircraft or ground forces. In the current aircraft, most of the information is transferred by voice communications. The copilot or observer often handles that task. The results obtained so far through operational and developmental testing indicate that the airborne target handoff system (ATHS) has the capability to transmit a large volume of data in a short period of time, but one member of the dual-crew aircraft must devote considerable time to enter information into the system. The ATHS needs to become more automatic if used in the single-crew LHX.

From a human factors viewpoint, the crew workload and information transfer accuracy of communications sytems for the LHX must be improved considerably over current systems. The LHX should use an integrated communications control system in which all radios and navigation systems can be controlled from a single device. The task of entering data into the aircraft computer system, including a full CEOI should be automated in a user friendly way. The integrated communications display/controls must be designed to unburden the crew from the need to process through a large number of computer pages when desiring to transmit information. The noise levels in the system must be reduced and speech intelligibility increased to allow for a high probability that a message can be transmitted accurately the first time it is attempted. Automatic target handoff capabilities should be provided in which the information is gathered and transmitted with little crew interaction.

7. SURVIVABILITY.

Aircraft survivability equipment (ASE) will be an important factor in the success of the LHX. The threat possesses a formidable array of ground and airborne systems that can be used against Army aircraft, including the individual soldier's hand-held weapons, radar and optical guided missiles, heat-seeking sensors, electronic countermeasures (ECM) and attack helicopters, and fixed wing aircraft. The primary defense against many of those weapons will be threat avoidance. When complete avoidance is not possible and the LHX is detected, the next defense is to prevent the threat weapon from reaching the aircraft by using evasive maneuvers or countermeasures. The defensive techniques and methods for survivability are as varied and as numerous as the threat they are expected to encounter. Countermeasure aids fall into two major categories: detection and jamming/decoys. A capability should be available in the LHX time frame for detecting threat systems expected to be encountered on the battlefield of the future. Jammers should, likewise, be available for radar, lasers, and IR systems. Flares and decoys are also expected to be part of the LHX defensive system.

The detailed capabilities of each of those systems is covered elsewhere in the TOA. The concerns from the human factors standpoint are the ability of the aircrew to react to these devices and take the appropriate corrective action to avoid becoming a casualty.

The first area to consider is complete avoidance of the threat. To accomplish this, the aircrew requires information concerning the threat type and location. Some of the information will hopefully be provided to the aircrew before starting the mission. Provisions for entering known threats into the LHX computer memory and the display of those threats on a situation awareness display, along with geographic location information must be available to the aircrew. The aircrew can then plan their flight course around those threats. Provisions should also be made to update that information during flight through information automatically provided from other aircraft or ground systems, the onboard sensors, and manually by the aircrew. ASE detectors and countermeasures must be kept to a minimum. For the LHX to react rapidly to the threat, the automation of some countermeasures should be considered. The pilot should, however, have an override capability that allows him to control the ASE when automatic activation may be a disadvantage. For example, the LHX will only be able to carry a limited quantity of chaff and decoys. To conserve these resources, the crew should decide when and where to use them. A fully automatic system may dispense them too rapidly and at a less than optimal time.

The LHX will operate in a highly lethal environment of combined air and ground threats. The aircrew must, therefore, be provided with effective threat detection and countermeasures so the LHX cannot only survive on the battlefield, but stay and fight. These systems should provide a capability to detect and counter threats located completely around the aircraft, as well as below and above it. Current ASE does not always provide that full capability. For example, an air threat behind the LHX, when not radiating a detectable signal, may not be detected by the aircrew engaged in battle. ASE significantly enhances the chances for both the aircraft and crew survivability and mission success.

ASE hardware and software developments appear to have kept pace with most of the threat but through dedicated individual systems. The integration of the ASE for simplistic presentation to the aircrew, in a prioritized format, is essential for a single-crew aircraft. It is recommended that an analysis be conducted to determine the degree of integration necessary and to determine the most effective method for information presentation, how it should be displayed and when it should be displayed. In addition, ASE countermeasures should be considered for automation.

8. TARGET ACQUISITION/DESIGNATION.

One of the most important combat functions of the SCAT version of the light helicopter fleet is target acquisition and engagement. A high level of automation must be incorporated into the LHX to allow the SCAT to accomplish that function. Advanced technology must be fully integrated into the crewstation to maintain the crew workload at a manageable level that will permit mission success. The current capabilities of target acquisition and engagement systems in Army aircraft are reflected in the AH-1 Cobra and AH-64 Apache attack helicopters. Those systems were designed to perform the target acquisition and engagement function in the air-to-ground role. During the attack mission, the pilot of those two-crew aircraft flies the aircraft and maneuvers it into the proper position to engage the enemy. The targeting function is assigned to the copilot/gunner who is totally occupied with the target acquisition and engagement task. The workload of both crewmembers during the attack mission is relatively high. The single-crew LHX will only become a reality if major technology advances are available to reduce the workload level of the two crewmembers down to a level that can be handled by one.

The sensors that are available in the Apache attack helicopters include direct view optics (DVO), day television systems (DTV), and a forward-looking infrared system (FLIR). The DVO and television systems are used mainly during the day. The FLIR system is useful during periods of reduced visibility and at night. The target acquisition and designation systems in the Apache directly places the sensor data and aircraft weapons information on both the pilot and copilot/gunners display. The success of the target acquisition and engagement systems on current attack helicopters is therefore fully dependent on the combined abilities of the two-member crew.

The candidate sensors for the LHX, include DVO, video/television sensors, IR devices, and radar. Much like the Apache, the video/television and DVO can be used during daylight. The FLIR and radar systems can be used during the day and at night. One of the major factors that will influence the overall success of the LHX target acquisition and engagement capability will be the maturity level of the various sensors needed to acquire and provide information concerning the type of target and its location on the battlefield.

The second part of the equation involves the methods and systems used to pass that information on to the aircrew. As mentioned earlier, the attack aircraft in the field today require a crew of two to be effective. How well the LHX target acquisition and engagement system operates is dependent on the consideration given to human factors engineering criteria and the soldier-machine interface. To reduce aviator workload and facilitate the target acquisition and engagement task, a faster, more sophisticated method of data processing and correlation must be developed for the LHX. The ideal system would be one that fully automates the target detection, acquisition, tracking, identification, and engagement tasks, and provides a capability to automatically pass target information to other members of the combined arms team. The level at which these functions can be successfully automated will significantly impact the crew size of the LHX. From the human factors viewpoint, the automatic processing of the various sensor inputs to provide a composite display which only contains the information necessary for target engagement or handoff should do much to ease the crew workload.

Target tracking should be automated to assist in holding the target within the FOV of the sensor and displays and reduce pilot workload when performing that function. The systems should automatically compute target location and range with respect to the aircraft and geographic position. That information, along with target identification information, should be automatically transferred to the communications system and transmitted to other friendly forces. Expansion of the sensor visual scene through a number of FOV selections should be provided to allow the aircrew to better see and examine specific targets or points of interest. The FOV changes associated with that expansion should be as gradual as possible to allow the operator to continuously track the target.

Recordings of the information obtained through the sensors would provide a capability for the aircrew to only expose their aircraft for a short period of time, obtain a picture of the battlefield, return the aircraft to a safer position, and then play back the recording obtained. The full extent of this capability has not yet been evaluated, but it would assist in increasing the survivability rate of the LHX by permitting a more detailed examination of potential target data in a less vulnerable position. The recording capability would also be of considerable use to collect information during reconnaissance misions and to assess battle damage after an attack.

The methods for displaying the target visual information that appear to be within the LHX technology time frame are twofold: a panel-mounted display (PMD) and a helmet-mounted display (HMD). The PMD, by itself, is a poor option for a single-crew LHX because it requires the aviator to keep his head inside the crewstation. The HMD system will be a necessity for the single-crew LHX where the pilot must keep his eyes outside the crewstation as much as possible. One disadvantage of the HMD is the large variety of information the pilot needs to have on that display to fly the aircraft and to perform the targeting function. The aircrew could be easily inundated with too much information. The alternative would be a combination of PMDs and HMDs. The PMD in the crewstation could display the detailed information from the targeting system sensors individually or as an integrated composite. Portions of that information could be extracted and placed on the HMD to provide the minimum information required by the aircrew. If the system were fully automated, the aircrew would need only enough information to assure the process was operating correctly.

Human factors standards and handbooks provide considerable data concerning visual limitations and criteria with respect to the design of display characteristics. The major challenge for the LHX is not necessarily in that area but one of meaningful integration of the sensor inputs that will provide the aircrew the information needed without creating a workload level they are unable to cope with.

Target sensor systems will also be required to automatically scan for airborne targets, as well as ground targets. That capability should include a 360°-target search completely around the aircraft.

The target acquisition and engagement in current Army attack helicopters is a two-crewmember task. For a single-crewmember LHX to effectively accomplish that mission, a major leap in sensor capabilities and the automation of many of the target acquisition and engagements must be accomplished. That automation should cover all functions from initial target detection until engagement of the target. In addition to the current activities associated with air-to-ground targeting tasks, the LHX crew must also contend with air-to-air target acquisition and engagement tasks. Based on the technology assessments presented so far, not all of the target acquisition and engagement functions can be automated, in particular target recognition. The aircrew will be expected to make the final confirmation that the target is the enemy and make the decision to engage the target. From the human factors perspective, the concept of multisensor fusion or integration and the display of the composite results have not yet been evaluated in sufficient detail to allow a valid prediction of its capabilities or limitations. A number of development efforts are underway but they are still in the early stages. Further efforts in this area are required to make a single-crew LHX a reality.

9. AVIATION LIFE SUPPORT EQUIPMENT.

Aviation life support equipment (ALSE), including protective gear, also plays an important role in aircrew survival in combat. In addition to the NBC protection previously discussed, ALSE includes:

- Protective helmets
- Flight suits
- Armor panels and vest
- Aircraft environmental control systems
- Oxygen systems
- Laser and nuclear eye protection
- Cold weather clothing
- Survival gear and radios
- Weapons.

The protective helmet not only contains the system by which the aircraft can communicate within and outside the crewstation but also provides head impact protection during a crash, and provides environmental noise attenuation to protect the aviators ears. Unless the LHX is radically different than previous aircraft designs, similar protection will still be necessary. Future helmets should also include laser and nuclear flashblindness protection unless that protection can be built into the aircraft itself. Add to this the wide FOV HMDs expected in the LHX and the helmet system becomes more complex. The LHX helmet with all the above systems and NBC protection added will be much different than present helmets. The new aircrew integrated helmet, now under development, integrates impact, noise, laser, NBC, and flashblindness protection into one helmet but it is not addressing the HMD issue. An advanced LHX helmet development program needs to be initiatied to address this issue.

Protective armor is another area where the LHX design could do much to alleviate the performance degradations associated with those devices. Aviators now fly with armor protective seats and armor vests. The vests are bulky, heavy, and restrict aircrew movements. The LHX should consider additional armor protection as part of the aircraft so that the amount worn by the aircrew could be reduced. When it is necessary for the aircrew to wear body armor, the LHX crewstation configuration must take into consideration the restricted movements of the aviator while wearing such armor.

The environmental control systems, heating, and cooling ventilation in today's fleet fall far short of providing the optimal environment for the aircrew to operate in. The net result is increased aviator stress and fatigue that degrades mission effectiveness or time. Systems have been and are under development that can overcome this problem if applied to the LHX crewstation design.

Oxygen systems are required for the LHX to allow operations at altitudes above 10,000 feet mean sea level, such as that found in mountainous terrain. During night operations, oxygen has also been found to greatly increase night vision capabilities at a few thousand feet above sea level. Due to the logistics problems associated with bottled oxygen systems, it is recommended that the LHX have an onboard oxygen system designed into the aircraft. Such systems that are presently flying in Air Force and Navy high-performance aircraft could be adapted to the LHX for that purpose.

Improved flight suits, cold weather clothing, survival gear, and survival radios are all being developed under Army and tri-Service programs, not directly related to the LHX. Those programs should mature independently of the LHX. The LHX crewstation design must, however, take into consideration the space constraints required for that ALSE. The crewstation controls and displays must, for example, consider operation by aviators dressed in bulky cold weather clothing. When wearing survival gear, the aviator's movements will also be restricted. The LHX should, at a minimum, consider building some of the survival gear into the aircraft seat so aviators do not have to wear it on their body. The LHX design must also provide storage space for ALSE that must be stored on the aircraft, in-flight, and on the ground when not in use.

10. DISPLAYS AND CONTROLS.

The method in which information is displayed to the aircrew of the LHX and the controls provided to operate the mission equipment and systems is perhaps the most crucial aspect of the crewstation design. As mentioned earlier, the increased demands of the Army 21 concept, coupled with the continued addition of new and more complex systems into the helicopter crewstations, are rapidly approaching a point where crew workload or attention demands may prevent obtaining the maximum effectiveness from the aircraft capabilities. Studies have shown that when flying at terrain flight levels, particularly NOE, the pilot's visual attention concentrated outside the crewstation varies from 33 to 80 percent of the overall available time, depending on the mission profile. This leaves little time to monitor the displays and controls within the aircraft.

To assure success in the AirLand Battle, aircrew workload must not be allowed to exceed a level that restricts the effective use of full aircraft capabilities. The best aircraft system available is of little use unless it can be effectively operated by the aircrew. One solution for reducing the variety and quantity of individual displays and controls is the use of a fully integrated electronic cockpit. That approach replaces the many cockpit displays, toggle switches, push buttons, rotary switches, and electromechanical meters and gauges with TV-like displays and electronic keyboard controls. The potential advantages of an integrated electronic crewstation when designed for effective human interface are--

(1) The capability to provide the relevant data required by the crewmembers in the most accessible panel areas of the crewstation.

(2) A reduction of the forward instrument panel space required for displays, thus improving the out-of-cockpit visibility.

(3) The use of flight computers to partially relieve the aviator's mental workload by integration of raw flight data into a form that requires less dedicated displays.

(4) A reduction in the weight of existing aircraft systems by combining current functions, supported by a number of black boxes, into one less bulky system.

(5) A reduction of the number of controls presently in the cockpit.

Displays combined with the visual capabilities of the aircrew and the sensors feeding them provide the information to support the basic mission functions of spatial orientation, flight path control, weapons delivery, survivability, navigation, and aircraft systems monitoring. Each of these functions places demands on a portion of the aviators attention during a typical LHX mission. The mission success will therefore be much dependent on the manner in which that information is presented to the aircrew and the division of the aviator's time to properly attend to each of these functions.

One concept for the presentation of visual information in the LHX is the use of a wide FOV panoramic display, mounted in the aircraft in front of the aviator, that would display aircraft performance information superimposed on an image of the outside world, with resolution and visual capabilities that are similar to that of the human eye. It is recognized that the technology development for such sensors and displays has not yet reached a maturity level that would allow that to occur and reportedly will not do so within the constraints, goals, and time frame of the LHX. The two visual display options that appear to be available for the LHX are helmet-mounted and panel-mounted displays. The attributes of each will be covered in more detail.

The use of a helmet-mounted display in the LHX that would allow the aviators to keep their eyes outside the crewstation, while simultaneously having mission information displayed on a see-through lens in front of their eyes could provide a significant advantage when flying NOE and when acquiring and destroying targets. In both those flight modes, while performing the pilotage or a targeting task, much of the aviator's attention is concentrated on things outside the crewstation with little time to monitor displays in the crewstation. The helmet-mounted display, when integrated with a head-sensing system and weapons control, would also provide a means to rapidly slew weapons and/or weapon sensors by means of head movements.

Two of the major design criterion that need to be established for the helmet-mounted display is the FOV and the field of regard (FOR). The ideal FOV and FOR for helmet-mounted displays, from the human factors engineering standpoint, would be one that approaches that of the human visual system. The assessment of current technology indicates that full capability will most likely not be available for the initial fielding of the LHX and, therefore, some smaller FOV and FOR must be considered.

There is little in the way of scientific data to establish the exact requirement, but a number of evaluations point to the need for wide FOV considerably larger than that of current systems. Flight and simulation studies, along with aviator assessments, suggest that the FOV for HMDs should be considerably greater than the 40° available in current systems.

The estimated FOV needed for the LHX, reported in the U.S. Army Aviation Systems Command (USAAVSCOM) Trade-Off Determination (TOD), was 110° horizontal by 60° vertical. The wide FOV permits the aircrew to acquire peripheral information that can be helpful in flying the aircraft and detecting threats. Evaluations conducted in conjunction with the ongoing "LHX Virtual Cockpit" assessment, conducted by the Air Force Aerospace Medical Research Laboratory (AFAMRL), indicates experienced Army aviators prefer a crewstation design that incorporates HMDs with a FOV that is at least 90° horizontal and 60° vertical or greater. FOV is not, however, the only factor in the ability to gain useful information from helmet-mounted visual disaplays.

Other factors such as resolution, contrast, brightness, and refresh rates are involved. The wider FOV is best, given that all these other factors are constant but this is not always the case. The LHX HMD parameters will be a compromise between a number of criteria. The FOV will, therefore, be determined by the capability of the technology available in the LHX time frame to provide a wide FOV while maintaining a level of image quality that enhances human and mission performance.

The workload analyses of the Advanced Rotorcraft Technology Assessment (ARTI) program support the need for a wide FOV display for the LHX. Preliminary information from the ARTI program received to date indicates that a 90°- by 60°-FOV appears to be within the realm of possibility. This area needs to receive considerable attention to assure the resultant LHX design is mission effective.

In addition to the FOV requirement, the sensors providing information to the HMD should be slewable to provide a field of regard that approaches the aviator's capabilities at movement rates commensurate with normal head movement. With such a visually coupled system, the visual content of the HMD would correspond with the aviator's head and aircraft movement. The limiting factor will again be the capability of technology to provide the maximum FOR.

The physical location of the sensors providing information to the aircrew is also important. The sensor itself should be positioned as close to the reference action position of the crewmember's eye as possible to reduce errors in judgment concerning aircraft location. Sensors that are located at some distance from the position of the aviator's eyes require the aviator to mentally manipulate the information he sees on his display in order to react properly to that information. The net result is a requirement for increased initial training and the need to fly with the system more often to maintain an acceptable skill level.

The reported disadvantages of the HMD from the human factors engineering viewpoint include the limited amount of information that can be placed on the display, helmet weight, and connecting cables that may impede egress from the crewstation in an emergency, a lack of easy interchangeability of tailored helmets between aviators, the considerable time consumed in fitting the helmet to the individual, and the time consumed in alignment of the sensors and weapon aiming sights. Each of these areas are critical and must be addressed in the LHX system design to reduce their negative impact on operational performance. A system design that allows for interchangeable helmets and display systems between individuals and between aircraft, would be best.

Panel-mounted visual displays provide a means to reduce the relatively large number of dedicated displays found in current aircraft to a few electronic displays. The information now placed on a number of individual dials and gauges could, for example, be integrated into a visual picture on one multifunction display. The major advantages of this approach, other than a reduction in space and weight, is the capability to place more visual information within the prime viewing space of the crewstation and require less head movement on the part of the aviators to obtain that information. This is important during flight to allow the aircrew to rapidly obtain information from the crewstation displays.

Voice generation and audio systems offer another approach for displaying information in the crewstation. Audio cues have been used for a number of years to gain the aircrew's attention during emergency situations and assist in the identification of flight and navigation aids. Those audio cues vary from a single tone or sound to the use of codes to identify radio signals. Synthesized voice generated by a computer, on the other hand, produces verbal messages that sound much like the human voice. It is an advanced means by which the aircraft systems can interact with the pilot while leaving his eyes free for obtaining visual information from outside the crewstation and from other displays. It is expected that a computer will be used to monitor the aircraft subsystems in the LHX. When the computer senses that a subsystems' tolerance limits have reached a level that requires pilot attention, a speech-generated signal could alert the pilot. Threat warnings could be handled in a similar manner either by speech alone or in conjunction with visual displays.

Speech generation technology is sufficiently advanced to a state that it could be used in the LHX today. The use of both generated speech and audio tones have a place in the LHX crewstation display system. Speech systems have the advantage of conveying information in a human-like voice, but do consume a dedicated amount of time and only one understandable message can be conveyed at a time. The audio tones, on the other hand, may be transmitted in a shorter period of time but requires the aviator to commit to memory the meaning of various coded tones. The use of generated speech or audio tones both have an additional limitation in that the human can only process a given amount of information in a short period of time. Too many speech or audio warnings, like any other warning system, could easily overload the aircrew. The advantages of both speech generation and audio tones need to be completely integrated with the visual information displays in the crewstation to provide the best transfer of information from the aircraft sensors to the human operator.

The effective design of the mission equipment systems controls placed in the crewstation is as important as the display system. It is through these devices that the aircrew communicates with and controls the operation of such mission equipment.

In the past, that function has been mainly accomplished by the use of dedicated toggle, rotary switches, and push buttons. These options, which are still available, can be supplemented with voice activated systems, touch sensitive electronic disolays, multifuction keyboards, individual push buttons, and joy sticks.

Each of these systems or approaches have been evaluated on a limited basis in the laboratory but few have received complete evaluations in Army aircraft.

The use of voice activated systems, for example, provides a potential that would allow the aircrew to control system functions by talking to the system. When the aviator speaks, the speech recognition system analyzes the spoken word and converts it into digital signals that can control aircraft systems. The major advantage of speech recognition is that it allows the pilot to interact with controls and displays using spoken commands without the use of his hands or feet. Potential applications of this technology include limited flight control such as "unmask" and "remasking" maneuvers, interaction with and possibly the firing of weapon systems, tuning and controlling of radios and navigation devices, and for data entry other than manual manipulation of a keyboard of switches. The above examples are but a few that speech recognition devices can support when the technology is mature enough to do so. At this time, the disadvantages of speech recognition are equally numerous. Research efforts have pointed out that speech recognition systems have problems when operating in a noisy envirnoment such as that of a helicopter. Emotional and physical stress effects on an individual's voice has an adverse effect on the system's ability to recognize the spoken word. Speech pattern differences between individuals is a major obstacle to the practical application of the technology. Today's systems are speaker-dependent, meaning that they must be trained to recognize the input of one particular speaker at a time. The potential for speech recognition to aid in reducing workload in the crewstations is high, but researchers in this area indicate the probability of its maturity within the LHX initial development is low.

Multifunction keyboards also provide a potential that should be captured for the LHX. As discussed in the section on communications, a single multifunction keyboard can be used to control a variety of radios and navigation systems thereby replacing a number of individual radio and navigation control heads. The major advantage is the reduction of space necessary in the crewstation devoted specifically to those control functions. From the human factors standpoint, the additional space provided by the use of a multifunction keyboard provides the feasibility to better place the remaining controls and displays in a position that facilitates their effective use by the aviators. Flying the aircraft with one hand while operating the multifunction keyboard may, however, present some problems. A multifunction keyboard has been used in the two-crewmember OH-58D scout helicopter but has not been evaluated in a single-crew context. This area needs to be more thoroughly evaluated.

The concept of the aviator keeping his hands on the controls as much as possible has received a lot of attention in the design of recently developed helicopters. That approach attempts to place all of the critical control switches on the cyclic or collective pitch grips so that the aviator can reach and operate them without moving his hands off the flight controls. Due to sensitivity of the side-arm controller, that approach may no longer be valid. It may be best not to put any system switches on the device. The aviators' free hand can then be expected to be used to operate the mission equipment and systems other than the flight controls. The location of the system controls therefore becomes an open question that requires investigation from a human factors viewpoint. This issue is of critical importance to the single crew LHX in order to maintain the crew workload at an acceptable level.

11. CONCLUSIONS/RECOMMENDATIONS.

Army aviation's role in combat has increased over the years from the relatively limited use of helicopters and fixed wing aircraft to transport soldiers and material around the battlefield and performing scout missions to one of full, close combat missions. The expanded missions along with the increased threat capability demanded the design and implementation of new tactics. Helicopters are now required to use terrain flight tactics to shield the aircraft from enemy detection. Flying at low levels and NOE below treetop levels is extremely demanding on the flight crew. NOE flight requires the pilot to focus most of his visual attention outside the crewstation while rapidly maneuvering the aircraft around obstacles in the flight path. Add the other crew tasks like navigating, communicating, target acquisition and engagement and monitoring of the aircraft subsystems, and the demand on the aircrew's physical and mental abilities rapidly increases. The requirement to fly and fight around-the-clock further compounds the problem.

The increasingly hostile environment Army aviators must fight in and the number and complexity of new aviation systems requires a large amount of information be presented to and assimilated by the aircrew. The most essential ingredient of the design of the LHX for the future battlefield is the integration of the vast amount of information provided by the aircraft sensors into a form that can easily be interpreted and used by the aircrew.

The goal of a single-crewmember LHX demands an even more efficient crewstation design. The full integration of the information displays, the control techniques employed, and the capabilities and limitations of the aircrew at a level much greater than current aircraft is mandatory, if that goal is to be achieved. The functions the aircrew must perform in the LHX fall into the major functional areas of flight control, navigation, communication, target acquisition and engagement, survivability, and system status monitoring.

Each of these functions is of prime importance when the LHX enters combat. The inability of the aircrew to effectively perform any one of these functions could result in degraded performance and loss of mission success. From a human factors viewpoint, the following general recommendations for the integrated crewstation should receive attention.

(1) Flight control. An accurate automated flight control with full terrain following and terrain avoidance capability would be best, but does not appear feasible within the LHX development schedule. The LHX should, however, provide a level of automatic control and stability augmentation that reduces pilot workload and improves mission performance. A hover-hold capability should be provided along with a low-level cruise capability. Consideration should also be given to an automatic "pop-up" maneuver control. The use of side-arm controllers to replace the current flight controls now found in helicopters also has some advantages with respect to aviator physical fatigue and the removal of visual restrictions between the aviator and the aircraft displays. The question concerning how many of the control functions can effectively be placed on a single side-arm controller remains unanswered. Additional investigations are needed to address that area.

(2) Navigation. The LHX navigation system should, at a minimum, consist of an electronic, horizontal situation display that gives the aircrew

real-time accurate, spatial information concerning their own position and the position of friendly and threat forces during day, night, and adverse weather conditions. The system should allow the aircrew to rapidly obtain information from the display with minimal head-down time inside the crewstation, provide a means to automatically update the position information, and allow the aircrew the capability to annotate the display with friendly and threat information. The feasibility and potential advantages of the digital data base navigation system should be included in the LHX when that technology matures.

(3) Communication. The control of the numerous radios and navigation aids from a central point should be considered to free up the crewstation space and allow a more effective placement of other displays and controls. The LHX design should include an automatic data loading system that would rapidly transfer communications, navigation, threat. and other system information into the avionics computers at the beginning of the mission and provide the capability of updating that information during flight. A communication system with less noise and better speech intelligibility needs to be developed for the LHX.

(4) Target acquisition and engagement. The automatic processing of information from the various target acquisition sensors, to provide a composite display which only contains the information necessary for target engagement or handoff, is recommended for the LHX. A fast method of data processing and correlation must be developed. Target lock-on and tracking should also be automated to assist in holding the target within the field of view of the sensor and displays. Video recording techniques should be employed to allow the aircrew to collect target or threat information for analysis at a later time. Sensors and related systems should be provided to automatically scan for airborne, as well as ground targets. The ideal would be a target acquisition and engagement system with full automation of the target detection, acquistiion, tracking, identification, and engagement task with the pilot as the system manager and final decision maker.

(5) Survivability.

(a) Aircraft survivability equipment (ASE) systems will be an important factor in the LHX. That system should have provisions for entering known threat information into the avionics computer memory and the display of those threats along with geographic location information should be designed into the LHX. Individual threat detection devices should be integrated to form a single survivability system that rapidly provides the aircrew relevant information regarding the threat location and the countermeasure necessary to defeat the threat. The threat information must be prioritized and the threats displayed must be limited to the optimal number the aircrew can handle at one time. The information presented to the aircrew should include target position and location, as well as information concerning the appropriate defensive action the crew should take to defeat the threat.

(b) NBC defensive measures must be a part of the crewstation design of the LHX to allow the aircrew the option to avoid contaminated areas or to fight in them. The system design should include NBC collective protection provided through a sealed and pressurized aircraft, remote detectors to warn the aircrew of contaminated areas before they have entered the area, and point detectors to advise the air and ground crews when the exterior or interior of the aircraft has become contaminated. The capability to maintain the individual aviator at the optimal body temperature while clothed in NBC clothing should also be included. The crewstation controls and displays should be designed so that they are compatible with the aviator in full NBC gear and life support equipment. In addition, the LHX design should consider agent resistant coatings and the application of design techniques to prevent contamination from adhering to the exterior surfaces and from entering the interior subsystems of the aircraft. Provisions should also be provided for the addition of onboard decontamination devices at a later date.

(6) System status monitoring.

Monitoring of the system status is a prime candidate for automation. It is recommended that the concept of system status management by exception be employed in the LHX. A computerized monitoring system could maintain a constant vigilance, perform trend analysis, diagnose abnormalities, and provide the aircrew with the information needed to take the appropriate action required by the particular situation. The system should also be designed to allow the aircrew the capability to obtain information from the system when desired.

(7) Aviation life support equipment (ALSE). The LHX crewstation should be designed so that the air and ground crews can effectively operate and maintain the aircraft when wearing cold weather, NBC, and survival clothing and gear. Space must be provided for the storage of ALSE. Oxygen systems should be provided for high altitude and night missions. An LHX advanced aircrew protective helmet should be designed as an integral part of the crewstation.

The detailed assessment of each of the nonmajor crew functions outlined above reveals a common denominator upon which the LHX mission performances and success heavily depends. The LHX sensors and systems all provide an enormous amount of mission-related information to the aircrew. The effective use of that information relies on the ability of the aircrew to mentally process the information, decide on the best course of action, and through the LHX controls, execute that action. To assure success of the LHX, information obtained from the various subsystems must be integrated and presented to the crew in a meaningful manner. The importance of the crewstation integration cannot be over emphasized.

This review of the major human factors engineering issues of the LHX crewstation integration concerns has indicated that the capabilities and limitations of the human must receive additional consideration. The LHX is expected to be a highly automated helicopter with the capability to provide the aircrew with information continuously. It is the integration of that information into the crewstation, along with the processing of that information by the crewmembers and the resulting control actions on the part of the aircraft that require much attention from the human factors engineering viewpoint. The human factors engineering analyses presented in the AVSCOM TOD and this TRADOC TOA, along with the preliminary results provided thus far from the ARTI program, all contribute to the assessment of the soldier-machine interface of the LHX and the enhancement of the crew's operational capabilities and the manpower, personnel, and training requirements. These preliminary efforts provide a framework for the development of the LHX but do not answer all the human factors engineering related issues. Human factors engineering for the LHX crewstation is part of an iterative design process that must be continually reviewed and updated. The operational success of the LHX on the battlefield is dependent on that process continuing. The continued support from a number of government organizations and laboratories that deal with human related aspects of Army aviation will be necessary to accomplish the LHX goals.

ANNEX R-III

TACTICAL IMPLICATIONS OF ONE-MAN VERSUS TWO-MAN AIRCREWS FOR THE LIGHT HELICOPTER FAMILY (LHX)

(Partial Report)

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Annex III to Appendix R

TACTICAL IMPLICATIONS OF ONE-MAN VERSUS TWO-MAN AIRCREWS FOR THE LIGHT HELICOPTER FAMILY (LHX)

(Partial Report)

R-III-1. The memorandum, "Tactical Implications of One-Man Versus Two-Man Aircrews for the Light Helicopter Family (LHX) (Partial Report)" is reproduced on the following pages. The memorandum was the result of a preliminary investigation conducted in the first half of 1983 by the Task Force 86 Division, Directorate of Combat Developments, United States Army Aviation Center, Fort Rucker, Alabama.

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DEPARTMENT OF THE ARMY
HEADQUARTERS UNITED STATES ARMY AVIATION CENTER AND FORT RUCKER
FORT RUCKER, ALABAMA 36362

REPLY TO
ATTENTION OF:

ATZQ-D-TF86 29 July 1983

MEMORANDUM THRU CHIEF, CONCEPTS AND STUDIES DIVISION, DCD

FOR DIRECTOR OF COMBAT DEVELOPMENTS

SUBJECT: Tactical Implications of One-Man Versus Two-Man Aircrews for the Light Helicopter Family (LHX) (Partial Report)

1. PURPOSE. To determine whether a one-man or a two-man aircrew is more tactically desirable for the Army's light helicopter family (LHX).

2. BACKGROUND. There is a concern among combat developers that while technology may be able to provide us a one-man cockpit for the LHX, the tactical implications of a one- or two-man aircrew in the context of the AirLand Battle have not been sufficiently identified or explained. The LHX concept formulation package (CFP) would require decisions on this, among other configuration problems, early enough to give the materiel developer and industry the guidance necessary to proceed with actual aircraft development. Therefore, the decision was made to identify these tactical implications. This memorandum records the results of a tactical function analysis. A second memorandum will be prepared later to record the results of the literature search and information obtained from sister services. Both memorandums will provide input to the LHX CFP cockpit substudy.

3. ASSUMPTIONS.

a. The LHX can have a fully integrated, one-man cockpit that will allow 24-hour, all-weather operations in time to meet its initial operational capability (IOC) date.

b. The LHX mission will require operation on a high-intensity battlefield in all-weather, day and night conditions.

c. The LHX-SCAT (scout attack) aircrew workload will be higher than that of the LHX-U (utility).

4. MISSION FUNCTION ANALYSIS.

a. Procedure. Rather than analyze the functions required for both LHX SCAT and utility crewmembers, the study team decided to analyze the mission which they considered the more demanding, that of the SCAT. The task analysis of the Advanced Scout Helicopter (ASH) contained in the final report of the ASH Special Study Group (SSG) (reference 1) was used for the scout portion of the SCAT mission. This analysis was based on the 1986 battlefield and considered "the aerial scout in the air cavalry, attack helicopter, field artillery scout, and battlefield management roles." The study team added the attack functions, using the task analysis in the AAH COEA, (reference 2), not already covered. All of the functions were then adapted to the demands of AirLand Battle 2000 and analyzed on the basis of equipment expected to be available in the AH-64 and AHIP scout.

b. Results. Commanders tactically employ aircraft as an entire system. That system includes the airframe, the hardware, the control systems, and the aircrew. Tactically, it is irrelevant whether the aircrew consists of one crewman or two crewmen. What is relevant is that the system, including the aircrew, must be able to perform all the required battlefield functions. Those required of the SCAT are outlined below. If the SCAT system cannot perform even one of the functions, then it will be unsatisfactory for tactical use. Table 1 shows the relative importance of each SCAT function analyzed within the various SCAT roles--reconnaissance, attack, and field artillery aerial observer. The table also contains a summary of crew size required for each function using equipment expected to be available in the AHIP scout and AH-64. Following is the analysis of functions taken from the ASH CFP. The function, condition, standard, discussion, and related function paragraphs were extracted and adapted to the SCAT and AirLand Battle 2000. As much of the original wording as practical was left intact. We added paragraphs dealing with crew size and rationale. We also added functions 30 and 31, using information from the AAH COEA. Other function numbers remain the same as in the original ASH report. Assumption 3b applies to each function.

(1) Function 1: Detect military targets.

Condition: As an LHX SCAT with the aid of onboard long range and remote day/night and varying visibilities and weather.

Standard: Correctly recognize moving and stationary weapon systems by type; for example, tank, truck, or air defense weapon within the regimental area of interest.

Discussion:

AirLand Battle 2000 states that immediate and accurate detection of military weapon systems is essential to successful engagement of the enemy. First, the enemy must be detected and then recognized and further identified. Soviet doctrine dictates that they fight both day and night; therefore, US and Allied armies must be able to fight in the same environment.

Table 1. Importance of Functions in SCAT Roles (Primary or Secondary).

Function	SCAT Role			Aircrew Size Required*	
	Recon	Attack	FAAO	One Crewman	Two Crewmen
1	P	P	P		X
2	P	P	P		X
3	P	P	P		X
4	P	P	P		X
5	P	P	P		X
6	P	S	S		X
7	P	P	P		X
8	S			X	
9	P	P	P		X
10	P	P	P		X
11	P	P	P		X
12	P	P	P		X
13	P	P	P		X
14	P	P			X
15	P	P	P		X
16	P	P	P		X
17	P	P	P	X	
18	P	P			X
19	P	P			X
20	P	P			X
20A	P	P	P		X
20B	P	P	P		X
21	P				X
22	P	S			X
23	P		P		X
24	P		P		X
25	P	P	P		X
26	P	P	P		X
27	P				X
28	S	S	S		X
29	P	P	P	X	
30	S	P			X
31	S	P			X

*Requirement based on consideration of equipment expected to be available in the AHIP scout and AH-64.

Timely detection of targets in the area of interest is extremely important to the frontline commander. Commander's reaction time to critical situations is essential to timely execution of maneuver to counter a threat. Increased identification ranges increase valuable reaction time.

Related functions: 26, 30.

Crew size: Two.

Rationale: One crewman is required to fly the aircraft, scanning rapidly the area in front of the aircraft while the other crewman does detailed, much slower search to the front for targets, using optical devices.

(2) Function 2: Recognize military targets.

Condition: As an LHX SCAT with the aid of onboard long range and remote sensors under day/night and varying visibilities and weather.

Standard: Correctly recognize moving and stationary weapon systems by type; for example, tank, truck, or air defense weapon within the regimental area of interest.

Discussion:

The AirLand Battle 2000 indicates that immediate and accurate recognition of vehicles and weapon systems is paramount to successful engagement of the enemy. Soviet doctrine dictates that Soviets fight both day and night; therefore, US and Allied armies must be able to fight in the same environment.

Timely recognition of targets in the area of interest is extremely important to the frontline commander. Commander's reaction time to critical situations is essential to timely execution of maneuver to counter a threat. Recognition at longer ranges increases valuable reaction time.

Related functions: 1, 26, 30, 31.

Crew size: Two.

Rationale: Same as function 1.

(3) Function 3: Identify military targets.

Condition: As an LHX SCAT with the aid of onboard long range and remote sensors under day/night and varying visibility and weather conditions.

Standard: Correctly identify moving and stationary weapon systems as friendly or enemy within the regimental area of influence.

Discussion: Battlefield effectiveness is highly dependent on timely identification of targets. Not only must a target be detected and recognized but also identified as friendly or threat by type and model such as Soviet tank T-72. Tanks require a different counter from infantry, for example. The frontline commander needs target identification as early as possible so that maneuver and preparation can be optimized. The joint TRADOC and TAC study, "Reconnaissance Surveillance Joint Mission Area Analysis" (reference 3), supports the requirement for rapid identification of targets. The importance of the identification increases as the distance from the friendly area of operations decreases. Commander's reaction time to critical situations is essential to timely execution of maneuver to counter a threat effectively.

Related functions: 1, 2, 26, 30, 31.

Crew size: Two.

Rationale: Same as function 1.

(4) Function 4: Communicate using tactical voice communications.

Condition: As an LHX SCAT using radios or data burst equipment.

Standard: Maintain communications with organic, supported, and supporting units.

Discussion:

Both the Air Force/Army Reconnaissance Force Study (reference 4) and the TAC/TRADOC Reconnaissance Surveillance Mission Area Analysis Study stress the immediacy of passing combat information to the team/task force frontline commander. This information acquired by the LHX SCAT must be provided on a timely basis, in most cases less than 5 minutes, accurate to 100 meters, and provide resolution that addresses threat vehicle type. Tactical communications provide the LHX SCAT with a means to convey timely, vital information to the responsible ground commander.

While this task specifically addresses communication requirements in terms of voice, it also recognized that systems such as TACFIRE and the battery computer system (BCS), while possessing a voice capability, will primarily emphasize digital communications. Digital communications will greatly contribute to reducing LHX SCAT voice communication requirements. However, digital communications will not eliminate totally the requirement for voice communications, particularly when unformatted information must be transmitted rapidly. It is acknowledged that voice communications can be jammed in an intense electronic warfare (EW) environment; however, as pointed out in the Nap-of-the-Earth Communications Concept Formulation Package, operation in a high EW threat environment requires radios to have advanced features such as variable power, preset channel selection, frequency scanning, selective-call codes, and a data transmission and receiving capability.

Related functions: 1-4, 12, 13, 18, 21-26, 28.

Crew size: Two, if information is formatted; one, if information is not formatted.

Rationale: Both formatting and inputting data require one crewman to transfer his attention from outside the aircraft to the format or data entry keyboard. The second crewmember is required to fly the aircraft and maintain aircraft security.

(5) Function 5: Communicate in an EW environment.

Condition: As an LHX SCAT faced with enemy EW.

Standard: Maintain continuous ability to receive, coordinate, and disseminate orders, requests, and combat information under the restrictive influence of enemy EW.

Discussion:

Current threat information indicates that the enemy has the capability to restrict or possibly prohibit electronic methods of communications. Further, that threat EW and physical destruction combined could possibly deny NATO forces the use of much of their electronic command and control systems before and during battle. Therefore, our communication systems must be varied and a certain amount of redundancy in communication systems will be necessary to maintain communications on the battlefield. In many instances, standard tactical voice communications will be available and should be used as required; however, these communication systems are easily susceptible to enemy jamming efforts and will not always be available. Because tactical voice communication systems can be jammed easily, an alternate communication system must be available to supplement tactical voice communications. One or more of the following systems must be available to supplement voice communications:

a. Digital message device (DMD). Difficult to jam because information is data burst to receiver in a fraction of the time required by voice communications.

b. Send-a-message (SAM). A visual method of communications in which different colors on flash cards indicate the message (see function 14 for details).

Studies and technology have shown that tactical voice communications can be improved for operation in a high EW threat environment by having features such as variable power, preset channel selection, frequency scanning, and selective call codes. However, these systems would still require one of the aforementioned systems as a back-up.

Related functions: 4, 6-8, 12-15, 18, 20, 20a, 21-26, 28.

Crew size: Two, if information is formatted; one, if information is not formatted.

Rationale: Same as function 4.

(6) Function 6: Pass battlefield information.

Condition: As an LHX SCAT via radio in an EW and non-EW environment utilizing voice and digital communications.

Standard: Combat information must be received by the frontline commander within 5 minutes. The report must include description of activity, size of force, speed, direction of movement and location to within a 100-meter accuracy.

Discussion:

The importance of spot reports increases with proximity to the FEBA and must be timely and accurate, otherwise the information accrues a "minus value." This minus value applies to information that has lost its utility and could cause unnecessary clogging of communication paths, wasted collection resources, and perhaps the blocking of other vital information. Combat information can lose its utility very rapidly when examined in light of company team/battalion task force commander's needs. Information within the area of influence for battlefield management purposes at the company team/battalion task force level must be timely to 5 minutes or less and identify company/platoon level threat unit location to 500 meters or less accuracy. Information for execution against the enemy within this area must be timely to the frontline commander to 5 minutes or less and must identify type threat vehicle locations to 100 meters or less accuracy. Precise locations and identities of specific weapons and weapon systems, communication modes and command posts as well as the identification, location, intentions, and strength of units are vital information to the battle captain fighting the war.

Aerial systems should be used to extend observation to the limit of the area of interest and to supplement capability of ground systems to observe close-in areas where terrain masking precludes direct ground observation.

Related functions: 4, 5, 7, 10, 20-22, 26-28.

Crew size: Two.

Rationale: One crewman flies the aircraft and maintains aircraft security while the other refers to maps, overlays, reference points, etc., in order to pass battlefield information.

(7) Function 7: Communicate during radio silence.

Condition: As an LHX SCAT without the use of radios during radio silence.

Standard: Maintain nonradio communications within organic, supported, and supporting units.

Discussion: It has long been recognized that radio silence is necessary at times to insure security, surprise, or protection against enemy EW. Traditionally, messenger service, visual communications, and sound communications have been used as alternative methods of communication during radio silence. Each of these three methods will be addressed individually below:

a. Messenger service is an excellent means of securely communicating during radio silence; however, this method, in many cases, may not satisfy the timeliness requirement for combat information which must be transmitted by the LHS SCAT. In many cases, this method may be the only method available to get valuable information to the commander. Additionally, the message service would require the LHX SCAT to return to an area suitable for handing or passing the information face-to-face or to dispatch a messenger to carry the information to the receiver.

b. Visual communications include flash cards, pyrotechnics (smoke, flares, lights), and hand and arm signals. Flash cards and hand and arm signals are used primarily to communicate within small combat units because this method of communication is generally limited to short distances and is dependent upon good visibility. Pyrotechnics can be used to signal information at greater distances but are also dependent on line of sight and visibility.

c. Sound devices can be effective over short distances but can easily be masked by battle noises.

It is important that the LHX SCAT be capable of employing non-radio communication techniques during periods of radio silence.

Related functions: 5, 6, 13-16, 18, 20-26, 31.

Crew size: Two for visual signals; one for messenger.

Rationale: Communicating during radio silence requires formatting of information if visual signals are used. Therefore, two people are required—one to fly the aircraft and maintain aircraft security and one to format the information and send it via visual signals.

(8) Function 8: Prepare radio relay.

Condition, standard, and discussion were classified SECRET in ASH CFP report.

Related functions: 5-7, 12, 13, 21-16, 28.

Crew size: One.

Rationale: Equipment onboard the aircraft relays information automatically.

(9) Function 9: Navigate/orient under day/night/reduced visibility.

Condition: As an LHX SCAT during day, night, and periods of varying visibility and weather conditions.

Standard: Navigate to and from given locations to perform tasks inherent to assigned mission.

Discussion: The Army Aviation Mission Area Analysis (January 1982) addresses current deficiencies and the need for effective navigation during day, night, and adverse weather. The threat is well prepared and trained to fight during periods of darkness and adverse weather. This will require LHX SCATs to be equipped with night vision devices, instrumentation, and precision navigation aids.

Related functions: 1-3, 18-22, 26-28.

Crew size: Two.

Rationale: One crewman is required to maintain aircraft attitude and security. The other crewman is required to read the map and maintain the correct location of the aircraft in relation to the battle.

(10) Function 10: Locate targets using universal transverse mercator (UTM) coordinates.

Condition: As an LHX SCAT under day/night and varying visibility and weather conditions.

Standard: Provide target locations to within 100 meters accuracy.

Discussion:

The standard system within the US Army for reporting the location of targets, as well as all other natural or man-made items, is the UTM coordinate system. This system is taught to all US Army combat soldiers and is the common Army language for position location. Consequently, if the LHX SCAT is to provide useful information to other Army elements, target locations must be expressed in UTM coordinates.

The requirement that targets be located with an accuracy of less than 100 meters is centered around the frontline commander's need for battlefield information, field artillery first-round fire-for-effect requirements, and procedures outlined for the AH-64 firing of HELLFIRE in the indirect mode. The Air Force/Army Reconnaissance Force Study stipulated that frontline team/task force commanders require, for the purpose of execution, target location to within 100 meters. This location criterion also includes the 100-meter bracket requirements for field artillery, thus allowing first-round fire-for-effect missions. In order for indirect HELLFIRE missions to be undertaken by the AH-64, precise target location information must be provided the system fire control computer to insure that the aircraft is aligned on the proper azimuth prior to missile launch.

Related functions: 12-14, 18, 21, 22, 26, 28, 30, 31.

Crew size: Two.

Rationale: Same as function 9.

(11) Function 11: Designate targets for hand-off to other LHX SCAT, attack helicopters, and tactical air using laser designator.

Condition: As an LHX SCAT with a laser designator during day/night and varying visibility and weather conditions.

Standard: Upon either detection, recognition, or identification, provide other LHX SCATs, attack helicopters, or close air support aircraft with laser designation and the necessary information for target acquisition.

Discussion:

Target hand-off via laser increases target servicing in a target-rich environment. Designation considerations include insuring the target is in the field of view of the receiver and is within range of the engagement system.

Target hand-off by a SCAT using a laser designator significantly reduces the exposure time of the engaging weapon system because there is very little acquisition and identification time involved. Target hand-off from a SCAT to another SCAT or an attack helicopter allows for autonomous engagement of a specific target by the attacking helicopter while freeing the SCAT to acquire other lucrative targets. Additionally, if a potential target's identification is in doubt, handing off the targe to another aircraft in a better position would allow for positive identification.

The ability of a commander to lase an object or a point on the ground by means of an aerial platform equipped with a laser designator and have that lased spot picked up by an aircraft equipped with an airborne laser tracker (ALT) in which a subordinate commander is riding, permits rapid coordination between commanders over matters such as establishment of boundaries and areas of responsibility.

The ability of a SCAT to hand off targets using a laser designator increases the attacking helicopter's survivability, facilitates the employment of a variety of Air Force delivered munitions, allows attacking helicopters to expend their ordnance from greater stand-off ranges, and affords senior commanders the opportunity to designate specific areas of responsibility to subordinate commanders.

Related functions: 3, 16, 25, 26, 30, 31.

Crew size: Two.

Rationale: The pilot is required to maintain aircraft attitude and local security. The other crewman is required to operate the designation device.

(12) Function 12: Hand off target to other LHX SCATs, attack helicopters, and tactical air using tactical voice communications.

Condition: As an LHX SCAT equipped with adequate tactical voice radios.

Standard: Maintain continuous ability to hand off targets within 40 seconds after recognition with the accuracy to allow for effective target engagement.

Discussion: Target hand-off consists of an alert, target description, target location, technique of attack, method of control, and execution. Timely and accurate target hand-off becomes increasingly important when the target is moving. Target hand-offs must be clear, concise, and in the proper sequential format indicated above. Currently, voice communication is the primary method for target hand-off during nonelectronic warfare conditions; however, in the future, digital communications will, to a great degree, replace voice-communicated target hand-offs to SCAT and attack helicopters. There will continue to be a requirement to hand off targets to tactical air and ground scouts by voice communications if these assets are not equipped with digital communication devices.

Related functions: 2-5, 7, 10, 16, 20A, 21, 22, 26, 30, 31.

Crew size: Two.

Rationale: Same as function 6. This function requires formatted information.

(13) Function 13: Hand off target to other LHX SCATs, attack helicopters, tactical air in an EW environment.

Condition: As an LHX SCAT equipped with a DMD faced with enemy EW conditions.

Standard: Maintain continuous ability to hand off targets within 40 seconds after recognition with the accuracy to allow for effective target engagement.

Discussion: As noted in function 12, target hand-offs are currently accomplished on tactical voice radios; however, enemy EW efforts will, at times, jam these communication systems. Hand and arm signals may be used during periods of EW, but these systems have line of sight and visibility restrictions which require the receiver to be in close proximity to the handing-off system. Digital communications are very effective for handing off targets during periods of EW because the entire hand-off is "data burst" to the receiver in a fraction of the time required for standard voice communications. Digital communications have other advantages in that crew workload is reduced, transcription and transmission errors are reduced, and hand-offs are standardized. These advantages will increase the probability of successful target engagement.

Related functions: 2-5, 7, 10, 12, 16, 20A, 21, 22, 26, 30, 31.

Crew size: Two.

Rationale: Same as function 6. Requires formatted information.

(14) Function 14: Hand off targets to other LHX SCATs and attack helicopters during radio silence.

Condition: As an LHX SCAT without the use of radios.

Standard: Hand off targets by means other than radio to attack helicopters and scouts. Hand off targets within 40 seconds following target recognition with the accuracy to allow for effective target engagement.

Discussion:

The target hand-off is normally accomplished by voice or digital communications (see functions 12 and 13); however, during periods of radio silence alternate target hand-off methods must be available and usable by the aerial scout. Nonradio target hand-off may include the following:

—The Send-a-message (SAM) system has been adopted by the US Army as part of a NATO effort to standardize other than radio transmissions. The SAM system consists of two sets of six colored and numbered flip cards which provides a total of 36 combinations of signals/messages that can be positioned so as to indicate a letter which in turn indicates the message; i.e., cards 3-3 indicate the letter O which means tanks. The same method is very effective within a small combat element where line of sight is available and visibility is not restricted. The SAM system may also be used at night with a series of dots and dashes from a flashlight to indicate the numbers.

Other systems have been developed at local levels, but the hand and arm system and the SAM system are the primary methods to hand off targets during radio silence.

Related functions: 5, 7, 13, 14, 28.

Crew size: Two.

Rationale: Same as functions 6 and 7.

(15) Function 15: Receive target hand-off via laser tracker.

Condition: As an LHX SCAT with a laser tracker during day/night and varying visibility and weather conditions.

Standard: Acquire targets that are adequately illuminated by laser designator.

Discussion: The ability to pass laser-illuminated targets from one system to another allows one system to acquire and illuminate a target and then pass this target to the SCAT's laser tracker. The procedure limits the exposure time of any one designator, improves target acquisition accuracy, and allows information transfer with minimum use of voice communications. All these factors serve to increase a system's survivability against the threat.

Related function: 26.

Crew size: Two.

Rationale: Full attention of one crewman is required to accept and continue tracking the target while the other crewman flies the aircraft. (This function is equipment-dependent; however, it is likely that either a laser tracker or some similar means will be provided for target hand-off.)

(16) Function 16: Designate targets for engagement by precision-guided munitions.

Condition: As an LHX SCAT with a precision laser designator during day/night and varying visibility and weather conditions.

Standard:

a. Provide adequate laser energy on target for employment of Army, Air Force, and Navy precision-guided munitions.

b. Ninety percent of the laser energy must remain on a standard tank-size target (7.5 X 7.5 feet or 2.3 X 2.3 meters) 95 percent of the time.

Discussion: This system will designate selected stationary/moving targets with laser illumination having sufficient energy and accuracy to achieve a high probability of a first-round hit by a missile/munition with a terminal homing laser seeker.

Related functions: 11, 25, 26.

Crew size: Two.

Rationale: Same as function 11.

(17) Function 17: Detect threat laser.

Condition: As an LHX SCAT equipped with a laser detection device during day/night and varying visibility and weather conditions.

Standard: Detect threat laser systems that illuminate friendly targets.

Discussion: Several modern Soviet weapons include laser range finders and laser target designators in their fire control systems. Both the T-72 and T-62 main battle tanks have laser range finders. Also, as outlined in open literature, the HIND attack helicopter, as well as the newer tactical fighters (MIG-27, SU-19), incorporates both laser range finders and/or target designators. These aircraft can be employed in the air-to-air or air-to-surface role. These laser systems can provide increased first-shot accuracy and precise terminal guidance for guided weapons. To counter this threat, the LHX SCAT must be able to detect threat laser energy in order to acquire the threat system that is illuminating it. Once the threat is acquired, the LHX SCAT, as a battle manager, can report the threat system or engage it. Laser energy detectors also serve in the secondary role of increasing LHX SCAT survivability. This warning must be accurate enough to allow proper evasive action. Evasive action has been proved effective against both tactical fighters and attack helicopters. While these tactics have been tested by helicopter units, they also apply to any airborne vehicle of like performance. The key factor in reaction to an airborne threat is a proper initial maneuver to counter the attack.

Related functions: 1-3, 10, 18, 20-22, 26.

Crew size: One.

Rationale: Pilot flies the aircraft and is visually cued. Only a cross reference to the instrument panel is required.

(18) Function 18: Select battle positions for other LHX SCATs or attack helicopters.

Condition: As an LHX SCAT during day/night and varying visibility and weather conditions.

Standard: Assess and select potential battle positions which provide adequate—

a. Cover and concealment.

b. Fields of fire at near maximum range.

c. Freedom from dust and debris.

d. Size.

Discussion: Attack positions, by doctrine, should provide sufficient concealment to allow the attack helicopter to avoid visual or radar detection. Cover must be available in the form of vegetation, terrain, or man-made objects. The fields of fire must allow for line of sight from the LHX SCAT or attack helicopter to the target without excessive unmasking. Battle positions must be near onboard weapon maximum range so that short-range enemy air defense weapons can be avoided. Areas which would produce an excessive dust signature must be avoided to insure that surprise is achieved. The size of battle positions will vary with the mission and number of LHX SCAT/attack helicopters using the battle position. The area must be large enough to allow the LHX SCAT/attack helicopter sufficient room to maneuver.

Related functions: 9, 19-21, 26.

Crew size: Two.

Rationale: One crewmember is required to fly and maintain local security of the aircraft. The other crewman records the information, does the detailed reconnaissance, and records and transmits the information to the attack aircraft.

(19) Function 19: Select ingress/egress routes.

Condition: As an LHX SCAT during day/night and varying visibility and weather conditions.

Standard: Select ingress/egress routes that provide maximum masking and/or stand-off for the attack helicopter.

Discussion: Attack helicopters are required to destroy and disrupt enemy mechanized forces. They must move about the battlefield in the shortest amount of time and with as much survivability as possible. The LHX SCAT selects ingress/egress routes to battle and firing positions while the attack aircraft are engaging the enemy. LHX SCATs can provide security and at the same time reconnoiter routes to the next firing position. The LHX SCAT can transfer this information to the attack aircraft by a variey of means, but the data must be relayed to the attack helicopters before it becomes usable input. Combined with the task of selecting ingress/egress routes are the tasks of detection of hostile elements and the selection of tentative battle and firing positions. Team leaders and higher commanders are better able to orchestrate the battle and mass against the critical sector when routes of movement are preselected and secured for the repositioning of attack helicopter assets.

Related functions: 9, 10, 20A, 20B, 21, 23, 26, 28.

Crew size: Two.

Rationale: Same as function 18.

(20) Function 20: Provide local security for other LHX SCATs, attack helicopters, and scouts.

Condition: As an LHX SCAT during day/night and varying visibility and weather conditions with the aid of sensors.

Standard:

a. Detect, recognize, and identify the threat.

b. Engage target or notify other armed helicopters.

Discussion: The primary threat to which the LHX SCAT will be regularly exposed because of its forward position on the battlefield is the SA-7 infrared (IR) guided missile and the ZSU-23-4 optical and radar-directed gun systems. In addition, most threat tanks mount a 12.7mm with an air defense capability. Sufficient numbers of these systems have been captured and exploited to essentially eliminate conjecture as to their capabilities. The LHX SCAT must be able to detect, recognize, identify, and either suppress or warn other team helicopters to seek cover and stand-off.

Related functions: 1-5, 7, 12-14, 17, 20A, 20B, 21, 22, 26.

Crew size: Two.

Rationale: Same as functions 1, 2, and 3.

(21) Function 20A: Engage threat aircraft.

Condition: As an LHX SCAT armed with a lightweight air defense missile during day/night and varying visibility and weather conditions.

Standard: Engage threat aircraft with an air defense missile.

Discussion: Large scale production of heavily armed Soviet helicopters will continue into 1985, and numerical superiority to US attack helicopters will be reached soon. Intelligence information indicates Soviet Hind crews training in mock air-to-air intercept and engagement of enemy helicopters. Procurement of ground air defense systems appears to be less than the density required to suppress the Hind. High performance aircraft which

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could suppress the Hind will be in high demand and have low availability to support ground operations. They will be able to gain air superiority for short periods of time over a small area and will be highly vulnerable to the threat air defense. High performance aircraft are also restricted in marginal weather when ceilings and visibilities are reduced. J-CATCH, a joint exercise with the objective of countering the Hind (reference 5), suggests the use of a lightweight air-to-air missile as an attractive option for the SCAT aircraft, which will extend the ground commander's counter-air capability.

Related functions: 1-3, 20, 23, and 30.

Crew size: Two.

Rationale: One crewman is required to fly the aircraft and maneuver it into a firing position. The other crewman maintains local security of aircraft and watches the area to the rear of the aircraft (6 o'clock).

(22) Function 20B: Perform suppression of enemy air defense.

Condition: As an LHX SCAT during day/night equipped with onboard missiles working in conjunction with attack helicopters or other Army air/ground assets during varying visibility and weather conditions.

Standard: Upon either recognition or identification of enemy air defense systems, immediately engage.

Discussion: Aerial firepower support systems are expected to face a massive array of air defense weapons in Europe. Overlapping coverage will be provided by the ZSU-23-4 antiaircraft guns and by SA-6, SA-7, SA-8, and SA-9 surface-to-air missiles clustered within divisional or regimental size units. With the large numbers of ADA weapons employed by the Warsaw Pact, the chances are that the SCAT working in conjunction with attack helicopters or ground forces will come "face-to-face" with some ADA weapons and because of the circumstances, have to employ organic AD weapons in order to survive.

Related functions: 20A, 26, and 30.

Crew size: Two.

Rationale: One crewmember is required to fly and operate offensive weapons and the other crewman to perform security of aircraft and, as needed, operate self-defense weapons.

(23) Function 21: Perform reconnaissance.

(a) Subfunctions:

1. Subfunction: Perform zone reconnaissance.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Successfully accomplish a detailed reconnaissance of all natural and manmade features within specified boundaries stated in operations orders. Reconnoiter all routes and terrain within the boundaries and if enemy contact is gained, develop the situation through reporting, maintaining observation, and, as required, fire and maneuver. Report all information rapidly and accurately to insure that the commander obtains the information with timeliness of 5 minutes or less, accuracy of sightings to 100 meters or less, and identification of type of threat vehicles sighted.

2. Subfunction: Perform area reconnaissance.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Successfully accomplish a detailed reconnaissance of an area specified in an operations order by a boundary line completely enclosing the area, i.e., a town, ridge line, woods, or controlling terrain. Emphasis should be placed on moving to the area rapidly. Enemy troops should be bypassed and reported. As in the zone reconnaissance, the area must be thoroughly reconnoitered. If enemy contact is gained, develop the situation through reporting, maintaining observation, and, if required, fire and maneuver. Report all information rapidly and accurately to insure that the commander to whom responsible obtains the information with timeliness of 5 minutes or less, accuracy of sightings to 100 meters or less, and identification of type threat vehicles sighted.

3. Subfunction: Perform route reconnaissance.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Successfully accomplish reconnaissance of a route as specified in the operations order to obtain detailed information of the route and all adjacent terrain from which the enemy could influence movement out to the range of direct fire weapons along the route. Orient the reconnaissance effort on a road, on an axis, or on a general direction of advance, whichever is indicated in the operations orders. Reconnoiter all dominating terrain features that could conceal enemy forces and terminate mission at the objective as indicated on operations order overlay. Determine and report class of bridges, location of roads and bypasses, clearance of overhead crossovers, width of slopes, composition of roadway, and depth of streams. Report all information rapidly and acurately and ensure that enemy information is reported so as to reach the commander to which responsible with timeliness of 5 minutes or less, accuracy of sightings to 100 meters or less, and resolution of recognition of type threat vehicle sighted.

(b) Discussion: Successful reconnaissance is mandatory on the airland battlefield. The continuous need for information increases with threat proximity to friendly positions and must be timely and accurate. According to recent studies, information for execution against the enemy with the regimental area of influence must be available to the front line commander within 5 minutes or less and must locate and recognize type threat vehicles to 100 meters or less. Battlefield management information on mobile targets is worth little if response time to the user is greater than 30 minutes.

Related functions: Other functions related closely to or a part of zone, area, and route reconnaissance--all.

Crew size: Two.

Rationale: Same as functions 1, 2, and 3.

(24) Function 22: Perform security operations.

(a) Subfunctions:

1. Subfunction: Perform screen mission.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Sucessfully accomplish requirements of the screen mission in conjunction with other elements of the screening force. Provide early warning of enemy approach by immediate reporting, gain and maintain enemy contact, assist in the destruction and repelling of enemy reconnaissance units, impede and harass the enemy by the adjustment of long range fires. Establish the initial screen line and withdraw to subsequent screen lines rapidly to ensure that gaps which may occur during withdrawal are quickly closed. If the operations order stipulates screening for a moving force, screen to the front, rear, or flank as directed by using the same general techniques and control measures as for the zone reconnaissance. However, the requirement for detailed information is less stringent than for the zone reconnaissance. As is true with reconnaissance missions, the screen also requires that information concerning the enemy must be reported so as to reach the commander to whom assigned or attached with timeliness of 5 minutes or less, accuracy of sightings to 100 meters or less, and identification of type threat vehicles sighted.

2. Subfunction: Perform guard mission.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Successfully accomplish requirements of the guard mission in conjunction with other elements of the guarding force, both air and ground. Provide early warning of enemy by immediate reporting, assist in developing the situation by gaining and maintaining contact, adjustment of fires, reconnoitering, and fire and maneuver, if required. Assist in protecting the main body from observation and provide maneuver room for the main body by reporting, adjusting direct and indirect fires, and maintaining contact with the enemy. Perform reconnaissance, screen, and be prepared to take part in an attack or defense with other air and ground elements of the guard force as the situation develops. If required to participate in the defense, provide the main body reaction time by immediate and accurate reporting, subject enemy to continuous attrition by autonomous fire and directing fires, destroy enemy reconnaissance, advance guard, and main force elements by directing artillery, tactical air, attack helicopter, and all other direct and indirect fire elements available.

3. Subfunction: Perform cover mission.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Successfully accomplish requirements of the cover mission in conjunction with other air and ground elements of the cover force. Standards listed above for the guard apply equally to the cover; however, the difference between the guard mission and that of cover is the scope of operations and the distance from the main body. The cover mission implies a tactically self-contained security force which operates at a considerable distance to the front, flank, or rear of a moving or stationary friendly force as stipulated in the operations order. The covering force must be prepared to develop the situation earlier, fight longer, and defeat larger enemy forces than the guard force. Reconnaissance is also a large part of the SCAT role in the cover and as such, the standards presented above for zone, area, and route reconnaissance apply here as well. As a member of the covering force the SCAT must be prepared to screen, guard, reconnoiter, attack, defend and, in general, fight as necessary by directing direct and indirect fires for mission success. As with the guard mission, reporting must be timely, accurate, and identify threat vehicle type. This is particularly important in the case where the covering force is unable to defeat the enemy, and the covered force must react to the threat.

(b) Discussion: Security missions are considered valid and necessary in AirLand Battle 2000. There is a need for the conduct of the screen and guard missions in any future conflict. Studies have been shown that forces with both air and ground elements are more effective in the screen and the guard than ground elements alone.

Related functions: All.

Crew size: Two.

Rationale: Same as functions 1, 2, 3, 3C, and 21.

(25) Function 23: Call for/adjust tac air.

Condition: As an LHX SCAT without a USAF FAC available during day/night and under varying visibility and weather conditions.

Standard: Request close air support using a standard request through the supported unit fire support coordinator (FSCOORD). Establish radio contact with the strike aircraft and brief pilots on the target type and location (within 100 meters) as well as friendly positions and threat. Provide the fighters an initial point (IP) in UTM or latitude/longitude for rendezvous, a magnetic attack heading to the target, and a time from IP to target. For aircraft carrying laser guided weapons without designators, the LHX SCAT must provide laser illumination of the target. After the air strike, estimate and report the bomb damage assessment (BDA) to the departing fighters.

Discussion: The tactical fighter is a flexible weapon system which can quickly destroy hard targets like tanks as well as cover large areas with lethal firepower. Tactical air strikes are usually controlled by a USAF forward air controller (FAC), who may be airborne or on the ground. As shown in the 1978 TAC/TRADOC Joint Air Attack Team Tactics Test (reference 6), the SCAT must be able to aid the FAC and fighters in target acquisition. In an emergency (no FAC available), the SCAT must initiate the close air support request through the supported unit's FSCOORD as well as guide the fighters to the target. The fighter flight lead determines tactics; the FAC/SCAT assigns targets and assures the safety of friendly units. Therefore, target location to within 100 meters is mandatory. Additionally, the FAC/SCAT must be able to express these locations in UTM and/or latitude and longitude because fighter aircraft have inertial navigation equipment and only occasionally carry UTM grid maps. The capability to adjust air strikes allows engagement of targets of opportunity after the attack begins. Strike aircraft may carry precision-guided munitions without a laser designator. Additionally, some fighers carry laser receivers that display illuminated targets on the pilot's sight. Both of these situations require target illumination by other sources such as a FAC/SCAT to employ the fighters properly. Finally, a BDA report updates the target information required by battle managers as addressed in the reconnaissance study.

Related functions: 1-5, 7, 20B, 21, 22, 26, and 28.

Crew size: Two.

Rationale: Same as function 12.

(26) Function 24: Call for/adjust conventional indirect fire.

Condition: As a LHX SCAT during day/night and under varying visibility and weather, subject to electronic warfare (EW) and non-EW environments.

Standard: Successfully gain and maintain communications with supporting artillery, request fires, adjust artillery rounds, and conduct battle damage assessment.

Discussion:

The requesting and adjusting of conventional artillery fires is a key task performed by the LHX SCAT. The SCAT in the field artillery aerial observer role focuses on the utilization of both indirect and precision-guided field artillery munitions. Tests and studies to date indicate that the SCAT, in the attack team leader role, may devote up to 60 percent of the time spent in the mission area to the management of indirect artillery fires.

SCAT wargames have shown that the missions assigned the SCAT frequently place him in the position of being the first element to acquire enemy targets. Consequently, the adjustment of long range indirect fires designed to harass, impede, and destroy enemy reconnaissance, advance guard, and main body targets become a primary responsibility of the SCAT.

Related functions: 4, 5, 7, 10, 20, 20B, 21, 22, and 26.

Crew size: Two.

Rationale: Same as function 12.

(27) Function 25: Call for/employ precision-guided munitions (PGM).

Condition: As an LHX SCAT equipped during day/night and under varying visibility and weather conditions.

Standards:

a. Successfully gain and maintain communications with supporting artillery, if other than autonomous fire is required.

b. Request fires, if other than autonomous fire is required.

c. Engage the target, if autonomous.

d. Conduct battle damage assessment.

Discussion:

Based on a variety of parameters, it may be determined that a specific target or target array can best be engaged with PGMs. When it has been determined what PGM is best suited for the target, coordination must be effected with the delivery system to ensure target destruction.

The following factors should be considered when determining if PGM (other than autonomous) should be employed:

a. Nature of target. Is it a lucrative target? Will it cause a choke point and slow the enemy advance? Is it a point or area target? Will added benefits be gained through surprise?

b. Location. Is the target within laser designation range for point target or area target? Can the elements of the employment algorithm be satisfied?

c. Intervisibility. Will smoke or battlefield obscuration interfere with laser designation?

d. Ceiling. Is the ceiling high enough to permit seeker lock-on and target engagement for nonautonomously delivered ordnance?

Related functions: 1-5, 7, 16, 21, 22, 26, and 30.

Crew size: Two.

Rationale: Same as function 12.

(28) Function 26: Operate in an NBC environment.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions on an NBC battlefield.

Standard: The SCAT must successfully accomplish all assigned tasks. Operators must be able to recognize existing NBC hazards, use protective equipment, and be able to decontaminate the vehicle and all personnel. Additionally, the vehicle must be able to survive in a nuclear environment of blast, over pressure, and thermal radiation using operator protection devices and normal sheltering. All vehicle maintenance and servicing tasks must be performed by protectively clothed personnel.

Discussion: The vulnerability of Army aviation to NBC agents has never been fully assessed even though the Soviet military is equipped and prepared psychologically for chemical warfare. Additionally, threat studies have indicated that nuclear weapons, if employed, will become their primary means of destroying US and allied forces. US Army aviation assets will be a primary target for all NBC operations because they pose a real threat to the main Soviet battle weapon—the tank. The SCAT system will face operations in a chemical environment of nerve, blood, and blister agents. In addition, friendly as well as hostile forces may be employing nuclear weapons. Therefore, the effects of blast and thermal energy must be considered. The most important requirement is preventing the loss of systems capability due to incapacitated operators. Shielding, protective clothing, masks, and early warning of NBC hazards must be provided.

Related functions: All.

Crew size: Two.

Rationale: Task relates to all other tasks; therefore, since most of the others require two crewmen, this one requires two crewmen.

(29) Function 27: Detect and identify contaminated areas.

Condition: As an LHX SCAT with onboard sensors and NBC recording equipment during day/night and under varying visibility and weather conditions, detect and identify NBC contaminated areas and conduct an aerial radiological survey as briefed by a divisional chemical officer.

Standard: Provide the divisional chemical officer the location and type of contamination and perform either a minimum time-simplified aerial survey or a detailed aerial survey. The minimum time survey will determine the outer limits of a militarily significant contamination area (2 rad/hour dose 1 hour after burst). The detailed survey will use course legs, routes, and point samples to provide sufficient ground dose rates to evaluate the contamination area.

Discussion:

The ability of the Soviet army to sustain NBC operations is unsurpassed. On the airland battlefield, friendly as well as hostile forces may be employing NBC agents that affect Army operations. It is mandatory that the commander have early warning of, and information about, the size of NBC affected areas. Detection and identification of the contaminated area are paramount to the commander's information needs. He must use this information to alter his plans. He may elect to protect his personnel and continue with his current plans. If that is the case, he must have more detailed information about the contaminated area. Therefore, a survey of some type is called for.

Two types of surveys are outlined--simplified and detailed. A simplified radiological survey shows the general limits of nuclear contamination in the least possible time. Also, it applies to areas where only limited information is available, such as enemy-controlled areas. The detailed survey is not time limited. It shows actual dose level contours and may include actual dose calculations for critical routes, points, and crossing areas.

Both tasks should be done by aerial means to insure timeliness of survey; minimum exposure for vehicles and/or personnel; and conservation of assets such as equipment, personnel, and communications time.

The simplified aerial survey is a flexible, quick reaction look at a militarily significant area. It has the advantage of providing information over a wide area and point ground data. The SCAT must be capable of slow speeds to adequately cover the area and of stopping for the purpose of taking point samples.

The detailed area survey is an in depth analysis of an objective area. It is performed in response to a map study requesting analysis of specific routes, areas, and points. The SCAT must be able to fly predetermined course legs to take dose rates at equidistant points. It must also be capable of taking point-ground readings to correlate with airborne readings. Recorded information will be forwarded to the requesting command level by the most direct communication means, in the current reporting format.

Related functions: 4-7, 21, and 26.

Crew size: Two.

Rationale: The pilot is required to fly and maintain heading and altitude. The other crewman is required to operate the sensor equipment.

(30) Function 28: Assist in search and rescue (SAR) missions.

Condition: As an LHX SCAT during day/night and under varying visibility and weather conditions.

Standard: Locate a survivor within 100 meters and communicate his position to other search systems. Act as the on-scene commander or provide any required fire support, personnel recovery, or search capability as directed by the SAR force commander.

Discussion: The need to recover lost personnel or downed aviators is a proven fact. Of the flyers downed over North Vietnam and Laos that were able to contact SAR forces, 80 percent were recovered. This recovery record was even better in the lower threat environment of South Vietnam. Because threat conditions, terrain, and weather vary, tactics and systems involved in a SAR effort may differ radically. A SAR mission may be a full-scale raid such as Son Tay or the quick recovery of a downed wingman. The basic concepts are standard. A mission into a high threat area requires a recovery vehicle, an on-scene commander, and search/fire support systems. The on-scene commander provides battle or recovery management for the force. Weapons on the SCAT can serve as the fire support system. The SCAT's basic mission is not changed by the requirement to search a given area for a survivor. Finally, the recovery vehicle mission can be accomplished by any platform with a landing, hoist, or hover capability combined with the power to carry additional weight. The capability to perform any or all of these SAR requirements is a valuable spin-off of other tasks.

Related functions: 4, 5, 7, 21, 26, and 30.

Crew size: Two.

Rationale: Same requirements as function 21.

(31) Function 29: Detect threat radar.

Condition: As an LHX SCAT equipped with a radar detection device during day/night and under varying visibility and weather conditions.

Standard: Detect, in azimuth and range, threat radar with accuracy and determine the type of radar-controlled system detected.

Discussion: The threat radar systems on the airland battlefield will be numerous and range from information-gathering, early warning systems to complex fire and aircraft control equipment. Radar system detection is a twofold requirement. There is a growing need to locate threat radar for front line commanders. The other function of a radar system's detector is warning of engagement by radar-controlled weapons, both air and ground. This requirement will increase system survivability. The SCAT operator is warned of the threat's attack direction by onboard sensors. Once detected in direction, the SCAT can initiate evasive action or engage the threat with organic weapons. The requirement to determine the type of radar system detected provides more detailed information for the battle management role. Also, radar detection ranges are greater than engagement ranges of threat weapons. Therefore, knowing the type of threat system will help the SCAT operator to take the best evasive or engagement action.

Related functions: 1-3, 19-22, and 26.

Crew size: One.

Rationale: Same as function 17.

(32) Function 30: Engage targets.

Condition: As an LHX SCAT armed with lightweight missiles during day/night and varying visibility and weather conditions.

Standard: After target detection and recognition, unmask and successfully track the target. Orient the aircraft to within missile parameters and launch the missile. For command-guided munitions, the aircraft must remain partially unmasked until missile impact. For fire and forget munitions, remask the aircraft and continue the mission.

Discussion: There is a variety of attack means available to the SCAT that will destroy a target. Depending upon the response time and availability, artillery and tac air are two means available. Hand-over to another direct fire system is also an option. However, sometimes it is desirable for the SCAT to engage a target with onboard weapon systems, by either direct fire or indirect fire. The most survivable is by indirect means; however, it requires the assistance of another system. Direct fire is the most accurate and time-sensitive engagement means. Should direct fire means be selected, fire-and-forget munitions contribute far more to survivability of the SCAT than command-guided munitions.

Related functions: 20, 20A, 20B, 21, 22, 25, and 26.

Crew size: Two.

Rationale: Same as functions 20A and 20B.

(33) Function 31: Call for or deliver and employ obscurants, illumination, and special effects munitions.

Condition: As an LHX SCAT equipped with voice and DMD communications during day/night and varying visibility and weather conditions.

Standard: Determine effect desired in consonance with the ground commander's scheme of maneuver. Determine the munition impact area to achieve the desired result. Call for indirect delivery or use direct deliver and adjust munition to achieve the desired result.

Discussion: The ground commander's scheme of maneuver may require the employment of obscurants, illumination, and special effects munitions. These munitions can be delivered by indirect means such as artillery, SCAT, or attack helicopters in defilade; this is the desired delivery technique. However, when time is critical or when communications cannot be effected between the observer and the delivery system, direct fire must be used to achieve the desired effect.

a. Obscurants. Obscurants are employed to conceal the activity of friendly forces. This can be to obscure the enemy's view while friendly forces withdraw to subsequent battle positions during the defense, or it could be used to obscure the enemy's view while friendly forces attack an objective.

b. Illumination. Illumination is used to illuminate the battlefield at night. It can be used to provide light for friendly operations, or it can be used to blind enemy optics and night vision systems.

c. Special effects munitions. Special effects munitions take the form of chemical incapacitants, concussion munitions, napalm, etc. These munitions can be used in a variety of ways based upon the ground commander's scheme of maneuver. They can be used to confuse the enemy or to deny him use of certain terrain which may give him the advantage over friendly forces during attacks for deep or close in objectives.

Related functions: 6, 20, 20A, 20B, 21, 22, 25, and 26.

Crew size: Two.

Rationale: Same as functions 20A and 20B.

c. Discussion of Functional Analysis.

(1) Looking at the SCAT system functions described above, intuitively the question of one-man cockpit versus two-man cockpit boils down to a tradeoff of workload between control systems and the aircrew, if one assumes that

the hardware and airframe are given. Further, if the hardware that performs or assists in performing the functions described above can be fully integrated so as not to overload the pilot, then the move to a one-man cockpit will require the integration of all systems early within the program. The "Band-Aid" approach that the military has taken for past aircraft will not work for a one-man system. The question then becomes, can the system be built which will perform the functions and not overload the aircrew?

(2) The next obvious step is to determine what the average pilot can handle without being overloaded. This step is necessary because it is highly likely that technology has exceeded the capabilities of the average human.

(a) For example, a pilot performing a reconnaissance function must maintain an overall picture of the battlefield. This picture is updated with every new piece of information that is received about the battlefield. The primary sensory perceptor for the pilot is the eye. The eye uses its macula vision to maintain the overall orientation of the battlefield and to detect targets or other information in the secondary search sector (more than 45° off of the nose of the aircraft). If specific information is displayed for the pilot to make a decision, then his attention is focused on that specific piece of information, and the overall picture of the battlefield is lost during that finite period of time in which his attention is diverted. This finite time period can be lengthy if his attention is focused on target engagements. The diversion of attention can be shorter if fire-and-forget munitions are used. However, if command-guided munitions are used such as TOW or HELLFIRE SAL, then the diversion of attention can get quite lengthy.

(b) Target engagement is probably the most physically taxing function to be performed. Body functions are at a higher rate than normal. An individual will be physically expended faster during repeated target engagements than during normal operations. Therefore, over a period of time, the crewman's ability to return to the overall battlefield picture and absorb it will be degraded.

(c) Another intense, heavy pilot workload is reconnaissance. Reconnaissance is very detailed and time consuming. The individual pilot, if in a one-man cockpit, will have a higher than normal physical exertion rate for a long period of time while performing this function. Therefore, if the pilot is presented several pieces of information about the reconnaissance sector, then it is highly likely that he will be overloaded with visual perceptors and will tire at a rapid rate.

(d) Technology must provide the means to avoid, lessen, or shorten these overload periods if the one-man cockpit is to work.

(3) If the decision is to build a two-man cockpit, then it is desirable to make it one-man flyable. If it requires two men to fly, then it will require two men to perform some one-man missions such as radio relay. While it is desirable to have two pilots on some missions, other missions may only require one pilot and one sensor operator, and still others may only require a pilot.

(4) The one-man cockpit must have growth potential. As the new battlefield is further defined in AirLand Battle 2000 and Focus 21, new battlefield functions will evolve that are not even conceived of today. These functions should be provided for in the cockpits that are built in the future.

5. CONCLUSIONS.

~~a. Whether a one- or two-man cockpit for the LHX is more tactically desirable is technology dependent~~.

a ~~b~~. A one-man cockpit is tactically acceptable provided technology can deliver a cockpit in which the pilot can perform every one of the SCAT functions described in paragraph 4a without being unacceptably overloaded.

b ~~c~~. If technology cannot provide for acceptable one-man performance of any one SCAT function singly or in combination with others as the mission requires, then a two-man cockpit will be required.

1 Encl
References

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ANNEX R-IV

A COMPUTER ANALYSIS TO PREDICT CREW WORKLOAD DURING LHX SCOUT - ATTACK MISSIONS

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Annex IV to Appendix R

A COMPUTER ANALYSIS TO PREDICT CREW WORKLOAD DURING LHX SCOUT - ATTACK MISSIONS

R-IV-1. The report, "A Computer Analysis to Predict Crew Workload During LHX Scout - Attack Missions" is reproduced on the following pages. The report was the result of an investigation conducted by Anacapa Sciences, Inc. for the U. S. Army Research Institute Field Unit, Fort Rucker, Alabama.

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A COMPUTER ANALYSIS TO PREDICT CREW WORKLOAD DURING LHX SCOUT - ATTACK MISSIONS

VOLUME I

PREPARED FOR:
U. S. ARMY RESEARCH INSTITUTE FIELD UNIT
FORT RUCKER, ALABAMA

OCTOBER 1984

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A COMPUTER ANALYSIS TO PREDICT CREW WORKLOAD DURING LHX SCOUT-ATTACK MISSIONS

VOLUME I

TECHNICAL REPORT

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Twenty-nine Light Helicopter Experimental (LHX) scout and attack mission segments were analyzed for excessive workload. Each of the mission segments was broken down into critical flight control, support, and mission functions, and positioned on a mission timeline. Functional analyses were performed by identifying the critical performance elements with their man-machine interface. Sensory, cognitive, and psychomotor workload and durations were estimated for each performance element.

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BLOCK 20. ABSTRACT - Continued

Computerized one- and two-crewmember models were developed. The mission and function analysis results, including the workload and duration estimates, were used as the data base. Decision rules were written for building (a) functions from the performance elements, and (b) mission segments from the functions. The computer models were used to predict total workload in four components: visual, auditory, cognitive, and psychomotor during concurrent performance elements.

Four methods of tabulating workload were devised. A computer program was developed to tabulate the four indices of workload termed (a) overload conditions, (b) overloads, (c) workload density, and (d) subsystem overloads. An overload threshold was established so that excessive workload could be identified throughout the missions. Performance elements and subsystems associated with excessive workload were identified. Results were used to compare the one- and two-crewmember configurations.

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The authors wish to express appreciation to several individuals who contributed to the LHX mission analysis and the preparation of the report. Captain Plint W. Hickman, of the U.S. Army Aviation Center's Directorate of Combat Developments, provided key information and documents for the LHX program. As the manager of the human factors man/machine integration for the LHX study group, he contributed many valuable suggestions throughout the conduct of the study. Dr. Will Bickley and Dr. Bob Wright served successively as the Army Research Institute's Technical Monitor. The authors are also grateful to Ms. Nadine McCollim and Ms. Tina Pridgen, Anacapa Sciences, for their extensive support in the formatting and typing of this report.

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INTRODUCTION

As part of its force modernization effort in aviation, the Army is evaluating the concept of a multipurpose, lightweight, experimental helicopter, designated the LHX. One of the major design goals for the LHX is that it should be capable of performing the scout and attack (SCAT) mission with a single crewmember. Some of the potential benefits of a single-crewmember design include:

- a lighter, smaller vehicle,
- increased survivability because of the smaller target profile,
- fewer pilot resources for manning the LHX fleet,
- lower training costs, and
- a greater number of flight hours achievable with a given aircraft to pilot ratio.

Improved and highly automated subsystems may make single-crewmember operation feasible. Some of the advanced design features being proposed for the LHX are:

- increased number of sensors and target acquisition aids,
- improved navigation and communication systems,
- advanced crew station design features,
- improved flight controls, and
- extraordinary avionics reliability, self-healing components, functional redundancies, and reconfigurable features.

Traditionally, the introduction of advanced technology into weapons system design has resulted in higher costs. However, extraordinarily high system reliability and single-crewmember operation may make the LHX cost effective.

The Army is formally evaluating the advanced development concepts for LHX in a series of trade-off studies and analyses. Human factors, man-machine interface questions are critical to the evaluation. All of the advanced design features listed above have human factor design implications. But, the primary human factors concern being addressed in the LHX trade-off studies is the feasibility of single-crewmember operation.

BACKGROUND

In a message from Commander, Aviation Research and Development Command (AVRADCOM), dated 7 July 1983, the Army Research Institute (ARI) Field Unit at Fort Rucker, Alabama, was tasked as the lead element to develop human factors analyses of the LHX scout attack (SCAT) mission. The message tasked ARI (a) to evaluate the feasibility of single-pilot LHX mission performance, and (b) to help identify the equipment operation and mission functions for which automation would be most beneficial. The AVRADCOM deadline for completing the work was 1 September 1983.

Dr. Jack McCracken of ARI developed the methodology described in a draft report and ARI Technical Note (McCracken & Aldrich, 1984). The chosen methodology includes a task analysis approach for analyzing the LHX mission and a subjective rating approach for estimating the workload imposed on the operator. Task analyses and subjective ratings are two of the commonly used methods for workload assessment. But, there are no known validated methods for predicting workload imposed by mission tasks in advance of system design.

Berliner, Angell, and Shearer (1964) offered a classification of Universal Operator Behavior Dimensions that is useful in deciding how to subjectively rate workload. Also useful is Wierwille and Williges (1978) classification of Workload Methodologies Dimensions. Their survey and analysis of Operator Workload Assessment Techniques and its companion annotated bibliography (Wierwille & Williges, 1980) document that no single technique can be recommended as a definitive method for measuring operator workload. Wierwille and Williges (1978) conclude that the multidimensionality of workload precludes assessment of workload with a single measure.

Attempts to predict workload, however, must rely solely on subjective opinions. There are no other measures available in advance of system design. Wierwille and Williges' recommendations for research focused attention on the problems encountered when collecting subjective opinions about workload. The Air Force's development of the Subjective Workload Assessment Technique (SWAT) (see Reid, Shingledecker, Nygren, and Eggemeier 1981), The Army's research at their Aeromechanical Laboratory (see Hart & Sheridan, 1984), and work at Virginia Polytechnic Institute and State University (see Wierwille & Casali, 1983) are continuing attempts to develop reliable and valid rating scales for subjectively rating workload. The SWAT investigators and Hart agree that expert subjects have varying individual perceptions about what constitutes workload. Thus, ratings from expert subjects probably cannot be analyzed accurately without accounting for their individual differences as they perceive workload. Continuing research and further development of subjective rating methods for assessing workload may result in improved methods for predicting workload in advance of system design.

INITIAL ANALYSES

ARI responded immediately to the requirements in the AVRADCOM message. An analysis team, headed by Dr. Jack McCracken (ARI), with contractor support from Anacapa Sciences, Inc., completed a preliminary analysis in six weeks. A draft report and briefing, explaining the analysis, were presented to AVRADCOM on 30 August.

AVRADCOM immediately requested that ARI perform two additional analyses:

- an analysis assessing a high degree of automation for flight control, target search and acquisition, navigation, and weapon delivery functions (to be completed by 23 September).
- An analysis for a two-crewmember configuration (to be completed by 7 October).

The two additional analyses were completed and a draft report, subsequently published as an ARI Research Note (McCracken & Aldrich, 1984), was delivered to AVRADCOM during the first week in October 1983.

The three initial analyses satisfied the basic requirements set forth in the AVRADCOM Message. They provided a data base for evaluating the single versus dual-crewmember configurations and various automation options. Excessive workload demands on a single crewmember were identified during the baseline analysis with no automation, and compared with results from the two additional analyses. Results indicated that single-pilot operation in the LHX will require considerable automation of crew functions. The iteration with an assumed high degree of automation resulted in the reduction of excessive workload to brief periods in only three mission segments during nap-of-the-earth (NOE) flight. The baseline iteration with two crewmembers resulted in the elimination of excessive workload from only seven of the 29 mission segments. Excessive workload was reduced dramatically for the crewmember performing flight control functions, but frequent, excessive, workload remained for the other crewmember performing support and mission functions. The two-crewmember analysis indicated that some automation will be required even if the two-crewmember LHX configuration is selected.

PURPOSE AND RATIONALE

The results from the initial analyses were rudimentary, but they achieved three objectives by providing:

- a method for evaluating the feasibility of single-pilot operation of the LHX during scout-attack missions,
- analytical material for identifying equipment operations and mission functions where automation can reduce pilot workload and enhance mission performance, and
- approximate first-iteration estimates of workload and performance times at the function level of analysis.

However, the analyses cover only three basic configurations:

- single crewmember, no automation,
- single crewmember, high degree of automation, and
- two crewmembers, no automation.

The LHX trade-off studies require several additional analyses to evaluate system and subsystem design alternatives. Each design alternative will have impact on operator workload and can affect mission effectiveness. Rather than treating automation as an all or nothing proposition, the studies require rapid response in analyzing the various options so that the optimal mix of automation and crew composition can be identified. Estimates of such impact must be produced accurately and quickly.

Data automation is essential for achieving the timeliness and accuracy required if subsequent iterations of the mission analyses are performed in phase with the LHX program milestones. Accordingly, the

Commander, AVRADCOM, provided funds on 1 October 1983 to the ARI Fort Rucker Field Unit for the establishment of a computerized data base for LHX mission analysis. The ARI Field Unit directed Anacapa Sciences, Inc., to perform the following tasks:

- Program the ARI computer to support entry of mission analyses data and LHX system, subsystem, and mission equipment data.
- Enter mission analyses and system, subsystem, and mission equipment data into the computerized data base.
- Develop or obtain software, including a simulation model for evaluation of the impact of various systems, subsystems, and mission equipment design alternatives on crew workload and performance times.
- Perform evaluative analyses and provide recommendations regarding the impact of design alternatives on human performance and emerging requirements for LHX aviator training.

Anacapa investigators completed the first task by adapting methods used during the earlier analyses. The one crewmember, no automation analysis was repeated using data automation to produce a data base for use in future iterations. Entry of the initial mission analyses into the computerized data base represents completion of the second task. This report presents the results of these efforts and limited comparisons between the single-crewmember and two-crewmember computerized analyses.

METHOD

This section of the report describes the methods and procedures used to accomplish two analytic tasks--both aimed at generating estimates of (a) the workload that LHX crewmembers can be expected to encounter in a one-crewmember and a two-crewmember aircraft, and (b) the extent to which overloads can be reduced by various types and levels of automation. The first task described consists of a series of manual analyses; that is, analyses conducted without the aid of a computer. The second task, which is a logical extension of the first, consists of a series of computer analyses. As is discussed in more detail later, the computer programs were developed to generate workload estimates with greater precision and greater speed than is possible with the manual analyses. It is important to emphasize, however, that both analyses address the same mission functions and employ the same subjective estimates of the level of workload imposed by individual tasks that LHX crewmembers must perform to accomplish these mission functions.

MANUAL ANALYSES

The following paragraphs outline the methods and procedures used to perform the manual analyses for three LHX configurations:

- one crewmember, no automation,
- one crewmember, high degree of automation, and
- two crewmembers, no automation.

The procedures presented in the following subsections correspond to steps in the analytic process.

- identification of mission phases and segments,
- identification of mission functions and performance elements,

- estimates of workload imposed by performance elements, and
- tabulation of concurrent and sequential workload demands.

The data generated by the first three steps of the manual analyses (McCracken & Aldrich, 1984) were used with minor refinements for the computer analyses. The manual analyses and the computer analyses differ significantly only in the fourth step. The differences are discussed in the appropriate subsections.

Limitations

In developing the methodology, certain limitations were established at the start. The limitations listed below apply to both the manual analyses and the computer analyses.

- Since specific subsystem design has not yet occurred, subsystems and procedures were viewed in non-specific, generic terms.
- The specificity level of the analyses was limited to the identification of general human performance elements within the mission functions. (The terms "mission function" and "performance element" are defined in a later subsection.)
- Analyses addressed only primary aeroscout and attack mission functions under normal operating conditions. System failures, visual obscuration, or enemy countermeasures were not addressed.
- Validation of the analyses was limited to content review by subject matter experts.
- Time estimates, workload estimates, and other parameters of the mission functions were based upon the analysts' understanding of current Army doctrine and tactics.
- When estimating workload for the non-automated LHX configuration, the general level of subsystem and weapon technology was assumed to be comparable to that available in the latest Army helicopters, the OH-58D and AH-64A.

Identification of Critical Mission Segments

Twenty-four LHX (SCAT) profiles, prepared by the Directorate of Combat Developments at the U.S. Army Aviation Center (DCD, undated), were examined at the start of the mission analysis. The 24 missions are actually two sets of 12 basic missions. One set consists of 12 missions in a European scenario; the other set consists of the same 12 missions in a Mid-East scenario. A careful study of the missions led to the conclusion that the function level of analysis would not be sensitive to the differences between the two sets of missions. Therefore, the European set of 12 missions was selected for analysis. The 12 missions are:

- anti-armor,
- anti-personnel/materiel,
- special operations/strike,
- reconnaissance,
- security,
- deep strike,
- rear area consolidation operation (RACO),
- suppression of enemy air defense (SEAD),
- amphibious assault,
- forward aerial artillery observation (FAAO),
- air-to-air (defense), and
- air-to-air (offense).

The mission analysis commenced with a thorough study of the mission profile developed for each of the 12 missions by the Aviation Center's Directorate of Combat Developments (DCD, undated). Project personnel then subdivided each mission into mission phases and subdivided each mission phase into mission segments. The component phases of a mission included all or a portion of the following: preflight, departure, enroute (outbound/inbound), reconnaissance, target servicing, forward area arming and refueling, terminal operations, and postflight. Mission segments were defined by examining changes in the type and purpose of the crew's activities during the mission phase. That is, the boundaries of mission segments were established at points throughout the mission phase at which the type or purpose of the crew's activities change significantly.

At this stage of the analysis, it became clear that an in-depth workload analysis of every segment of every mission phase was neither feasible nor necessary. Accordingly, the purpose of the next task undertaken was to select a limited but representative sample of mission segments for further analysis. The primary factors considered in selecting the sample of mission segments include: the estimated likelihood of crew overloads, the estimated incidence of crew overloads, the estimated severity of overloads, and the estimated consequences of overloads. Experienced Army aviators and experienced research personnel contributed to the final selection of the mission segment sample.

The mission segments selected for detailed analysis are shown in Table 1. The "X"s signify the segments selected and the mission and mission phase from which the segment was drawn. It should be noted that no segments were selected from three missions (strike-special operations, security, and rear-area consolidation operations [RACO]). It should also be noted that no segments were selected for four of the eight mission phases (preflight, departure, forward-area arming and refueling, and postflight). The net result is that 31 segments were selected from nine different missions and four different mission phases.

Identification of Functions

A brief comment about excessive workload is needed to introduce this subsection. It is generally recognized that excessive workload may

TABLE 1

MISSION SEGMENTS SELECTED FOR IN-DEPTH ANALYSIS

		SCAT MISSIONS											
MISSION PHASE	MISSION SEGMENT	ANTI-ARMOR	ANTI-PERS./MAT.	STRIKE (SPECIAL OPS)	RECONNAISSANCE	SECURITY	STRIKE (DEEP)	RACO	SEAD	AMPHIB. ASSAULT	FAAO	AIR-TO-AIR (DEFENSE)	AIR-TO-AIR (OFFENSE)
ENROUTE	LOW LEVEL FLIGHT									X			
	CONTOUR FLIGHT						X						
	NOE FLIGHT						X						
RECONNAISSANCE	ESTABLISH OBSERVATION POINT										X		
	TACTICAL MOVEMENT	X			X						X		
	SURVEY										X		
	REPORT										X		
TARGET SERVICE	ACQUISITION		X						X			X	X
	ENGAGEMENT	X	X						X			X	X
	HANDOFF								X			X	X
	ADJUSTMENT		X						X				
	TEAM COORDINATION								X			X	X
	TACTICAL MOVEMENT		X						X			X	X
TERMINAL	RECOVER TO LANDING ZONE									X			

be the result of (a) the requirement to engage in a single activity that exceeds the operator's capacity in some way, (b) the requirement to engage in two activities concurrently that, together, exceed the operator's capacity, (c) the requirement to perform sequential (non-overlapping) activities in a limited amount of time, or (d) some combination of these. As a consequence, it is essential that workload estimates take into consideration the workload associated with individual activities, the extent to which activities overlap in time, and the time within which the activities must be completed. The analyses described in this subsection were designed to provide information with which to address such factors.

Each of the 31 segments was dissected into "functions" that must be performed, either by a human operator or by an aircraft equipment component, in order to complete the segment successfully. The functions were then classified into one of three categories and placed on a rough timeline. The three categories of functions are as follows:

- Flight Control--functions associated with flying the aircraft. Examples include hovering, maneuvering NOE, and unmasking.
- Mission--functions associated with achieving combat objectives, such as acquiring and engaging targets.
- Support--functions performed in support of flight control and mission functions, e.g., checking systems and threat warning displays, navigating, and communicating.

A segment summary sheet was developed with separate columns for categorizing each function. Table 2 is an example of a segment summary sheet depicting functions performed during an air-to-air engagement. The critical flight control functions are listed in the FLIGHT CONTROL column in the sequence most likely to be followed in an air-to-air

TABLE 2

SEGMENT SUMMARY WORKSHEET

Phase Target Service, Air-to-Air

Segment 25: Engagement Air-to-Air Method From Masked Position

FLIGHT CONTROL	SUPPORT	MISSION
Hover Masked	Check A/C Systems	
Unmask Sensor		
		Track Target
Align Heading on Target Bearing		
		Estimate Range
		Prepare Weapon
Unmask Aircraft		
		Track Target
		Fire Weapon
Deploy to Cover		

engagement. The essential support functions are listed in the SUPPORT column, and the essential mission functions are listed in the MISSION column. The vertical listing is analogous to a timeline, but has no precise time scale. Listings located on the rough timeline depict temporal relationships among the flight control, support, and mission functions. In Table 2, for example, the support function "Check Aircraft systems" is depicted as being performed concurrently with the flight control function "Hover Masked"; the mission function "Track Target" is depicted as being performed subsequent to the flight control function "Unmask Sensor."

Four rules were followed in preparing the segment summary sheets:

- Functions should be listed only if they are judged critical for accomplishing the specified mission activity or if they must be performed on a recurring basis in support of the mission activity. In Table 2, the support function "Check Aircraft systems" is not strictly critical to performance of the mission activities, but must be performed on a recurring basis.
- Initiation times of functions must reflect typical temporal sequencing. To the extent possible, initiation times of functions should be delayed to avoid concurrence and, thereby, minimize workload.
- No more than one function within a single category can be performed at the same time. However, functions from two or three different categories can be performed concurrently. For example, no segment summary sheet depicts two flight control functions being performed concurrently. However, support and/or mission functions are depicted as being performed at the same time as flight control functions.
- A flight control function must be performed at all times throughout the segment.

Current aeroscout and attack mission doctrine was adhered to in identifying the critical functions and locating them on the segment summary worksheets. Aircrew Training Manuals and existing task analyses were used as references.

Segment summary sheets were initially prepared for each of the 31 segments identified in Table 1. Additional summary sheets were prepared for some segments to depict alternative methods of performance. This increased the total number of segment summaries to more than 40. Several segment summaries contained virtually identical functions; they differed only in the order in which the functions were listed. Eliminating such duplicates reduced the number of segment summary sheets to 29. The 29 segments selected for further analyses are included in Appendix A.

Analysis of Functions

The 29 segments selected for further analyses contain 58 different functions. Each of the 58 functions were dissected into "performance elements" considered critical to successful performance of the function. Each performance element is defined in terms of a verb and an object. The verb describes the action; the object describes the recipient of the action. For example, the performance element "Follow Course" denotes a specific crew activity. Appendix B is a glossary of verbs and objects used in the analyses.

The performance elements are the basic elements of the mission analyses and are equivalent to the task level of specificity in traditional task analyses. Each performance element was analyzed to:

- identify the generic subsystem presenting the primary man/machine interface,
- estimate the workload imposed on the operator, and
- estimate the length of time required to complete the performance element.

Identification of the generic subsystems was based upon knowledge of the manner in which similar tasks are performed in existing Army helicopters. Methods of estimating workload and performance times require some explanation.

Workload, as the term is used in these analyses, has three components: sensory, cognitive, and psychomotor. The sensory component refers to the complexity of the visual or auditory stimuli to which an operator must respond. The cognitive component refers to the level of thinking required, and the psychomotor component refers to the complexity of the behavioral responses required. It is important to note that workload, as estimated in this analysis, is not limited to overt behavior. A considerable portion of aviators' efforts, especially in combat missions, consists of sensory intake and cognitive processing. The three-component concept of workload is well suited to account for these covert but important workload demands.

The scales shown in Table 3 were developed during the manual analyses (McCracken & Aldrich, 1984). The scale values indicate increasing complexity of the workload components. The analysts judged that the verbal descriptors denote an increase in complexity corresponding with the scale values. McCracken and Aldrich assigned scale values for each of the components of workload after all performance elements had been identified and listed with verbs and objects. The verb/object descriptors of the performance elements were compared with the verbal descriptors in the four scales presented in Table 3. The scale values for the Table 3 verbal descriptors most

TABLE 3

WORKLOAD COMPONENTS

SCALE VALUE	DESCRIPTORS
	VISUAL
1	MONITOR, SCAN, SURVEY
2	DETECT MOVEMENT, CHANGE IN SIZE, BRIGHTNESS
3	TRACE, FOLLOW, TRACK
4	ALIGN, AIM, ORIENT ON
5	DISCRIMINATE SYMBOLS, NUMBERS, WORDS
6	DISCRIMINATE BASED ON MULTIPLE ASPECTS
7	READ, DECIPHER TEXT, DECODE
	AUDITORY
1	DETECT OCCURRENCE OF SOUND, TONE, ETC.
2	DETECT CHANGE IN AMPLITUDE, PULSE RATE, PITCH
3	COMPREHEND SEMANTIC CONTENT OF MESSAGE
4	DISCRIMINATE SOUNDS ON THE BASIS OF SIGNAL PATTERN PITCH, PULSE RATE, AMPLITUDE
	COGNITIVE
1	AUTOMATIC (SIMPLE ASSOCIATION)
2	SIGN/SIGNAL RECOGNITION
3	ALTERNATIVE SELECTION
4	ENCODING/DECODING, RECALL
5	FORMULATION OF PLANS (PROJECTING ACTION SEQUENCE, ETC.)
6	EVALUATION (CONSIDER SEVERAL ASPECTS IN REACHING JUDGMENT)
7	ESTIMATION, CALCULATION, CONVERSION
	PSYCHOMOTOR
1	DISCRETE ACTUATION (BUTTON, TOGGLE, TRIGGER)
2	DISCRETE ADJUSTIVE (VARIABLE DIAL, ETC.)
3	SPEECH USING PRESCRIBED FORMAT
4	CONTINUOUS ADJUSTIVE (FLIGHT CONTROLS, SENSOR CONTROL, ETC.)
5	MANIPULATIVE (HANDLING OBJECTS, MAPS, ETC.)
6	SYMBOLIC PRODUCTION (WRITING)
7	SERIAL DISCRETE MANIPULATION (KEYBOARD ENTRIES)

clearly matching the performance element verb/object descriptors were assigned to the workload components in each performance element. The analysts reached consensus in their judgments and their consensus was reviewed by two subject matter experts.

Although performance element duration cannot be precisely determined in advance of hardware/equipment design, the time dimension is an essential component of workload estimation. Moreover, estimates of performance element duration were needed to develop a timeline. Therefore, the duration of each performance element was estimated and included in the analysis. The method used to derive the time estimates is described below.

Each performance element was categorized as discrete or continuous. Discrete performance elements are characterized by actions having a definite, observable start and end point. Activation of switches, performance of procedures, and radio transmissions are examples of performance elements considered discrete.

Existing helicopter task analyses were used in deriving estimates of discrete performance element duration. The task analyses used are listed below:

- OH-58D MEP Description and Workload Analysis, Bell Helicopter Report No. 406-099-063, Taylor, R. R. and Poole, R., 1983.
- Time Series Analysis for the AHIP, Applied Psychological Services, 1982.
- Time Series Analysis for the AH-64, Applied Psychological Services, 1982.
- Analysis of Control and Coordination During Helicopter Anti-Armor Operations, Holt, C. R. and Kelbawi, F. S., The Mitre Corporation Report No. MTR-82-W00022.

Time estimates for discrete LHX performance elements were estimated by (a) locating tasks in the reference material similar in content and mission context to the performance elements identified in these analyses, and (b) using the published times to estimate the duration of LHX performance elements.

Continuous performance elements do not have an observable start and end point and cannot be reduced to procedures; mission requirements and conditions determine their duration. Examples are performance elements that (a) require cyclic, collective, and pedal movements for controlling the helicopter, (b) require continuous movement of sensor joysticks for tracking targets, and/or (c) require continuous observation of terrain or target areas. Arbitrary duration times were assigned to such performance elements for these analyses. The arbitrary times were established by estimating the length of time necessary to accomplish discrete performance elements occurring concurrent with functions composed of continuous performance elements.

The following procedures were used in calculating total times for functions:

- Time estimates for all performance elements were rounded off to the nearest half second.
- A transition time of .5 second was inserted before each performance element when it was judged likely that an aviator would be in a performance mode requiring transition from the previous performance element.
- Time estimates were summed for all discrete performance elements in the function.
- Transition times between performance elements were added to the sum.
- Time estimates for continuous performance elements judged to overlap times for discrete performance elements were not added to the sum.

- Time estimates were adjusted to compensate for continuous performance elements partially overlapping discrete performance elements. The adjusted times were added to the sum.

A worksheet was developed for recording the results of the function analyses (Table 4). The verb and object for the performance element is listed in the two left-hand columns. In some cases, the object column includes modifying adjectives to provide additional information. The numbers in the verb column are the numeric identifiers used in the computerized data file. The generic subsystems associated with the performance elements are identified in the SUBSYSTEM column. A coding system (described below) consisting of one, two, or three letters was devised for identifying the subsystems in another computerized data file. Workload estimates are entered in the next three columns. Short descriptors of the sensory, cognitive, and psychomotor components are entered in these columns. Beneath each verbal descriptor, an alphanumeric code is presented in parentheses. The letters designate the type of workload component: V for visual, A for auditory, C for cognitive, and P for psychomotor. The number is the workload rating for the performance element (see Table 3). The time estimates for each performance element are listed (in seconds) in the DURATION column; this column also indicates whether the performance element is discrete or continuous. The COMMENTS column was used in the initial analyses to record total function time. However, in this report, the column contains the decision rules written to instruct the computer programmer on how to assemble the function from the performance elements in the data file. Function analysis worksheets for the 58 mission functions are found in Appendix C.

TABLE 4
FUNCTION ANALYSIS

FUNCTION Detect Target (Ground) No. 16

TOTAL TIME (APPROXIMATE) 20.5 seconds

METHOD Free Search Copilot

PERFORMANCE ELEMENTS			WORKLOAD COMPONENTS			DURATION (SECS) DISCRETE/ CONTINUOUS		
VERB	OBJECT	SUBSYSTEM(S)	SENSORY	COGNITIVE	PSYCHOMOTOR			COMMENTS
147 Search	Target area	Sensor display scene AS	Visual survey (V-1)	Area clear? (C-6)	Control pressure (LOS) (P-4)		12.5	Program PEs 147, 75, and 24 in sequence.
75 Detect	Movement	Sensor display scene AS	Visual detection (V-2)	Signal (movement) (C-2)		2		
24 Align	Sight	Sensor display/ sight ADS	Visual alignment (V-4)	Target Centered (C-2)	Control pressure (P-4)		5	

The last step in the function analysis was to review the 58 function analysis worksheets and decide how workload could be reduced by distributing crew functions between two pilots. The rule adopted for distributing crew functions is simple: flight control functions were assigned to one-crewmember and support and mission functions were assigned to the other crewmember.

The function analyses (Appendix C) were reviewed and divided into three groups. Twelve function analyses with flight control performance elements were assigned to the pilot group. Forty support and mission functions were assigned to the copilot group. Thus, 52 of the function analyses were divided, with flight control functions assigned to one crewmember and support and mission functions assigned to a second crewmember. The third group of six function analyses was judged to have performance elements likely to be performed by both crewmembers.

The 12 function analysis worksheets in the flight control group are annotated "Pilot" on the METHOD line. The 40 function analysis worksheets in the support and mission group are annotated "Copilot" on the METHOD line. The six worksheets for functions judged to have performance elements performed by both crewmembers are annotated "Both" on the METHOD line. The performance elements in these six function analyses have been further annotated to indicate whether the performance element is likely to be performed by the pilot, by the copilot, or by both.

Tabulation of Concurrent and Sequential Workload Demands

The primary objective of these analyses was to provide a data base for use in estimating the crew workload demand for different LHX configurations: single versus dual crewmember, and various levels of automation. The estimates of workload and the estimates of performance time provide the desired data base at the performance-element level of specificity. The data base can be used to estimate excessive workload caused either by (a) time pressure from sequential performance elements or (b) competing demands from concurrent performance elements. These analyses attended to the competing demands from concurrent performance elements. Worksheets were developed for tabulating the three components of workload and for identifying the concurrent demands placed on the operator. A sample worksheet entitled "Summary of Concurrent and Sequential Workload Demands" is presented in Table 5.

The summary of concurrent and sequential workload demands worksheet retains the basic format of the Segment Summary Worksheet (Table 2). The worksheet consists of four main sections. Three sections correspond to the major function categories of flight control, support, and mission. The fourth section presents the sum of the workload components across the columns. Each section is further divided into (a) a column for identifying the function, and (b) four small columns headed by the letters V (visual), A (auditory), C (cognitive), and P (psychomotor). Vertically the worksheet is a cumulative timeline with 10-second increments.

TABLE 5

SUMMARY OF CONCURRENT AND SEQUENTIAL WORKLOAD DEMANDS--SINGLE CREWMEMBER

Phase TARGET SERVICE, AIR-TO-AIR

Segment 24: ACQUISITION Method FREE SEARCH

	FLIGHT					SUPPORT					MISSION					TOTAL CONCURRENT			
CUM. SECS.	Function	V	A	C	P	Function	V	A	C	P	Function	V	A	C	P	V	A	C	P
10	25	2		1	4	06	5		2							7		3	4
20	54	2		1	4											2		1	4
30		2		2	4	35	2	2	2							4	2	4	4
40		2		2	4						32	1		3	4	3		5	8
50		2		2	4							4		4	4	6		6	8
60		2		2	4						15	4		6	4	6		8	8
70		2		2	4							2		4		4		6	4
80		2		2	4	49	5	1	4	3						7	1	6	7
90		2		2	4						27	3		3	4	5		5	8
100		2		2	4							4		5	4	6		7	8
110		2		2	4	20	4		1	4						9		6	12
120		2		2	4		6		6	4						11		11	12
130		2		2	4				7							2		9	4
140																			
150																			
160																			
170																			
180																			

The summary of concurrent and sequential workload demand worksheets enables reassembly of the functions in the sequence and relative time locations originally laid out on the Segment Summary Worksheets. Within the FUNCTION column, each function is identified by a two-digit number. The identification number corresponds to the function identification number listed in the table of contents for Appendix C; this number also appears on the corresponding function analysis worksheet. The summary worksheets present the results of the functional analyses by depicting the workload estimates (from the functional analysis worksheets) in the columns V, A, C, and P. The time estimates produced during the functional analyses were used to estimate the peak demand for each workload component during each 10-second interval. By presenting workload components for each 10-second interval, a sequential account of workload was developed throughout each segment. Total demand placed on the operator for each modality (V, A, C, P) during each 10-second interval is estimated by summing across corresponding entries to arrive at the totals in the right-hand column.

During the manual analyses, a summary of concurrent and sequential workload demands worksheet was developed for each of the 29 segments. They are presented in Appendix D.

The summaries are helpful indications of where a single operator's workload capacity may be exceeded. The numbers representing workload are best interpreted in relation to the verbal anchors shown in Table 3. For these analyses, level 7 was judged to be the upper boundary of human capacity in any single modality. Level 8 was judged to be an overload condition. Any value of 8 or higher in the summation column was judged to be an overload condition for these analyses.

The summary tables (Appendix D) were revised to depict the reduced workload that results from distributing the crew functions to two crewmembers; the revised summary tables are presented in Appendix E. The format was revised by dividing the cells with diagonal lines. Numbers to the left of the diagonal line represent workload demands on the pilot; numbers to the right of the diagonal line represent workload demands on the other crewmember. The timeline and basic organization of the summary tables were retained to enable direct comparison between the one-crewmember analysis and the two-crewmember analysis.

COMPUTER ANALYSES

From the start of the manual analyses in July 1983, plans were being formulated for development of computer programs and data files that would enable rapid analysis of various equipment automated options for the LHX crew functions and for comparison of the one- and two-crewmember configurations. Plans called for using the ARI Field Unit's Perkin-Elmer mini computer. FORTRAN 77 was chosen as the program language for the computerization effort.

The LHX trade-off studies being conducted by the Army require several additional analyses to evaluate design alternatives. Data automation provides the capability to perform such analyses rapidly and accurately. The workload estimates produced during the manual analyses provide available data. This section describes the steps taken to (a) enter the data into a computer data base, and (b) program the computer to perform the one-crewmember and two-crewmember, no automation analyses.

Work on the computer analyses began on 1 October 1983. Preliminary coding strategies, coding programs, data entry programs, and input formats were agreed upon on 2 October. The coding strategies, input formats, and computer programming efforts were directed at replicating the manual analyses of the one-crewmember, no automation configuration. Inconsistencies in terminology, time, and workload estimates from the manual analyses were resolved and standardized while planning for the data entry programs. Several data files were created as follows:

- a list of verbs and objects,
- a list of performance elements with estimates of workload and time,
- a list of functions,
- a list of segments, and
- a list of subsystem identifiers.

The manual analyses were developed using a top-down approach. That is, the analyses started with the identification of the missions and followed, top down, through the phases, segments, and functions to the performance element level. For the computer analyses, a bottom-up approach was adopted, with the performance elements serving as the basic elements of analysis.

The time estimates for all of the performance elements were rounded off to the nearest half second and a program was developed to produce a half-second timeline. The half-second timeline enables sequencing of the performance elements so that their appearance on the timeline closely resembles where they would likely appear in real flight. Thus, the half-second timeline provides an opportunity to build towards a computer simulation of the LHX mission segments. The next steps were to write decision rules for building functions from the performance elements, and subsequently, for building mission segments from the functions.

Decision Rules for Building Functions From Performance Elements

Decision rules were written for each of the 58 functions. They are presented in the Comments column on the function analyses worksheets shown in Appendix C. Decision rules for discrete performance elements define the sequence in which the performance elements are to be programmed. Consider, for example, Function 01, Acquire Position Data (see page C-4). The three performance elements, "Align Sight Reticle," "Activate Laser Range Finder," and "Note Coordinates," are discrete and would most likely be performed in the sequence presented. Thus, the decision rule simply states, "program performance elements 16, 4, and 122 in sequence."

Continuous performance elements have no definite start and/or completion time and often overlap other performance elements. Programs employing probability statements were developed so that performance elements likely to occur at the same time can be presented at alternating half-second intervals in accordance with a designated probability of occurrence. Decision rules incorporating this feature were written when judged appropriate. Function 09, Check Sighting (see page C-12) can be used as an example. The first two performance elements, "Monitor Surroundings," and "Survey Approaches to the AO," would normally be performed alternately throughout the 20-second time period. The decision rule, "Alternate PE's 111 and 192 randomly at half-second intervals, .50 probability," dictates that the computer randomly select one of the two performance elements each half second.

The decision rules also enable performance elements to be introduced at random times. An example is Function 18, "Establish Position" (page C-21). Performance elements "Check Position" (number 55) and "Check Obstacle Clearance" (number 43) would normally occur when necessary as an interruption to the performance elements "Maintain Obstacle Clearance" and "Follow Course." The decision rule "Interrupt at a randomly determined time with one sequence of performance elements 53 and 43 for 15.5 seconds..." dictates that the interruption occurs at a randomly determined time.

Decision Rules for Building Segments From Functions

More complex decision rules were needed to provide the necessary degree of realism in building segments from functions. The general guidelines listed below were followed in formulating the decision rules:

- A flight control function must always be present throughout the segment timeline.
- Function duration must be specified in every case.
- If a designated mission or support function cannot be completed during the time period designated for a mission segment, the mission segment (and the flight control function) must be extended for the amount of time needed to complete that mission or support function. Extend the time by selecting a single performance element in the function. (Performance element "Stabilize aircraft" was the performance element chosen most often for the time extension.)

- Flight control functions cannot overlap temporally.
- The onset of all mission and support functions must correspond with the temporal relationships specified on the segment summary worksheet.
- The duration of all support functions and mission functions must correspond with the durations specified on the corresponding function analysis worksheets.
- To the greatest extent possible, the onset of support functions must be adjusted to minimize workload and to avoid generating an overload condition.
- The onset of mission functions must be dictated solely by mission requirements.

The decision rules developed for building the 29 mission segments for the one-crewmember analysis are presented in Appendix F; the decision rules developed for the two-crewmember analysis are presented in Appendix G. The decision rules for building segments from functions include rules for the random selection of certain functions and rules for commencing certain functions at a randomly determined time.

Subsystem Codes

The LHX Mission Equipment Package (MEP) was used as a guide in classifying subsystems and in devising a subsystem coding strategy. In this way, the subsystems identified in the analysis are loosely tied to the subsystem classification being used in the LHX trade-off analyses. The major categories of subsystems in the MEP are:

- communications,
- navigation,
- flight control,
- target acquisition,
- aircraft survivability equipment (electronic),
- night vision pilotage, and
- controls and displays.

The major classes of subsystems used in the computer analyses are listed below.

- communication (C),
- navigation (N),
- flight control (F),
- fire control (I),
- target acquisition (A),
- aircraft survivability equipment (S),
- display subsystem (D),
- life support system (L),
- personal equipment/cockpit items (P), and
- visual field unaided (V).

The letter shown in parentheses is the first letter of the subsystem identifier code. A second and third letter was added to the first letter as necessary to identify the subsystem listing associated with the performance elements. Table 6 lists the codes and the associated subsystems.

The subsystem codes were entered in the performance element data file so that they can be readily identified when a performance element contributes to an overload condition.

Programming the Computer

Computer programs were developed to ensure that (a) the onset and duration of functions adhere to the decision rules established for building mission segments from functions, and (b) the onset and duration of performance elements adhere to the rules established for building functions from performance elements. The results of the manual analyses were used to validate the computer programs. Printouts of the mission segments were compared with the summaries of concurrent and sequential

TABLE 6

SUBSYSTEM CODES FOR GENERIC SUBSYSTEMS IDENTIFIED IN THE MISSION ANALYSIS

CODE	SUBSYSTEM
A	TARGET ACQUISITION SUBSYSTEM
AC	ACQUISITION SENSOR CONTROLS
ACF	ACQUISITION SENSOR CONTROLS/FOV
ACL	ACQUISITION SENSOR CONTROLS/LASER
ACS	ACQUISITION SENSOR CONTROLS/SIGHT
AD	ACQUISITION SENSOR DISPLAY
ADC	ACQUISITION SENSOR DISPLAY CONTROLS
ADS	ACQUISITION SENSOR DISPLAY/SIGHT
AK	TARGET KEYBOARD SYSTEM
AL	LASER RANGEFINDER
ALD	LASER DESIGNATOR
AR	SENSOR DISPLAY/RANGE
AS	SENSOR DISPLAY/SCENE
AT	SENSOR DISPLAY/TARGET CUE
C	COMMUNICATION SUBSYSTEM
CC	COMMUNICATION COORDINATION
CD	MESSAGE DISPLAY
CM	MESSAGE DEVICE
CR	COMMUNICATION SYSTEM/RECEIVE
CS	COMMUNICATION SYSTEM/SELECT
CT	COMMUNICATION SYSTEM/TRANSMIT
D	DISPLAY SUBSYSTEM
DE	ENGINE STATUS DISPLAYS
DEW	ENGINE CAUTION DISPLAYS
DF	FUEL SYSTEM DISPLAY
DT	THREAT DISPLAY/AURAL
DTV	THREAT DISPLAY/VISUAL
DM	MALFUNCTION DETECTION EQUIPMENT
F	FLIGHT CONTROL SUBSYSTEM
FAD	FLIGHT CONTROLS, SENSOR DISPLAY
FD	FLIGHT INSTRUMENTS
FP	POWER CONTROL
FV	FLIGHT CONTROLS/VISUAL
FVD	FLIGHT CONTROLS, VISUAL SCENE, DISPLAY
I	FIRE CONTROL SUBSYSTEM
ID	FIRE CONTROL DISPLAY
IP	FIRE CONTROL PANEL
L	LIFE SUPPORT SYSTEM
N	NAVIGATION SUBSYSTEM
NC	NAVIGATION CONTROLS
ND	NAVIGATION DISPLAY
NDC	NAVIGATION/COORDINATE DISPLAY
NDF	NAVIGATION DISPLAY/FLIGHT CONTROLS
NSM	NAVIGATION SENSOR SCENE AND MAP
P	PERSONAL EQUIPMENT/COCKPIT ITEMS
PC	CHECKLIST
S	AIRCRAFT SURVIVABILITY EQUIPMENT
SC	CHAFF DISPENSER
V	VISUAL FIELD UNAIDED
VD	VISUAL FIELD/SENSOR DISPLAY
VM	VISUAL FIELD/MAP
VND	VISUAL FIELD/NAVIGATION, DISPLAY

workload demands produced during the manual analysis. In some instances it was necessary to modify the computer programs and decision rules to make the computerized segment summary correspond with the manually generated summary of concurrent and sequential workload demands.

The extent of the programming load was underestimated when the computerization effort began. Originally, it was estimated that between 75 and 100 programs would be required to computerize the one-crewmember analysis. However, 170 separate programs were required before the computerization was completed. Programs provided both an 80 column terminal screen presentation and a 132 column paper printout program. The screen program lists only function numbers, whereas the print program lists the full names of segments, functions, and performance elements.

For the two-crewmember analyses, 220 separate programs were required to complete the computerization. The programs provide two 132-column paper printout programs, one for the pilot and one for the copilot. No terminal screen programs were written for the two crewmember analysis. The features in the print programs are presented in the Results section of this report.

RESULTS

Appendix H is the computer printout generated by the computer analysis of the one-crewmember, no-automation LHX configuration. Appendix I is the computer printout generated by the analysis of the two-crewmember, no-automation configuration. This section begins with a detailed explanation of (a) the printout's format, (b) the manner in which the printouts can be used to identify mission conditions resulting in probable pilot overload, and (c) the manner in which the printout can be used to identify candidate subsystems for automation. The remainder of the section describes (a) the types and frequencies of overload conditions revealed by the analyses, and (b) the degree of automation required to eliminate overload conditions.

THE PRINTOUT FORMAT

One-Crewmember Configuration

A sample page from the one-crewmember printout is presented in Table 7. This page was selected from the computerized version of the segment presented in Table 2 and again in Table 6: Engagement, Air-to-Air, From Masked Position. This allows some comparison among the Segment Summary Worksheet, the Summary of Concurrent and Sequential Workload Demands, and the computer-generated data depicted on the printouts. Following is a step-by-step explanation of the printout format. The numbers used in the following subheadings correspond with the circled numbers in Table 7.

TABLE 7

SAMPLE PRINTOUT FROM THE ONE-CREWMEMBER ANALYSIS

```
①SEGMENT NUMBER:  25
②SEGMENT TITLE :  ENGAGEMENT, AIR TO AIR, FROM MASKED POSITION
                 ③F L I G H T                 S U P P O R T                     M I S S I O N                  TOTAL        SUBSYSTEMS
④CUM. SECS. PERFORMANCE ELEMENTS  V A C P  PERFORMANCE ELEMENTS  V A C P  PERFORMANCE ELEMENTS  V A C P   V  A  C  P   F     S     M

⑤FN. NUMBER: 25
⑥FN TITLE   : HOVER MASKED
 ⑦108.5   ⑧CHECK CLEARANCE       ⑨1 0 2 0                                                                  1  0  2  0
   111.0    CONTROL DRIFT           2 0 1 4                                                                  2  0  1  4

  FN. NUMBER: 25                             6
  FN. TITLE : HOVER MASKED                   CHECK A/C SYSTEMS (PWR CHG)
 ⑩129.0     CHECK CLEARANCE         1 0 2 0 ⑪ADJUST POWER         0 0 1 0                                  ⑫1  0  3  0
   130.0     CHECK CLEARANCE         1 0 2 0   CHECK SYSTEMS        5 0 2 0                                   6  0  4  0
   131.5     CONTROL DRIFT           2 0 1 4   CHECK SYSTEMS        5 0 2 0                                   7  0  3  4

  FN. NUMBER: 25
  FN. TITLE : HOVER MASKED
   140.5     CHECK CLEARANCE         1 0 2 0                                                                  1  0  2  0
   143.0     CONTROL HEADING         2 0 1 4                                                                  2  0  1  4
   164.5     CHECK CLEARANCE         1 0 2 0                                                                  1  0  2  0
   167.0     CONTROL ALTITUDE        2 0 1 4                                                                  2  0  1  4

  FN. NUMBER: 54
  FN. TITLE : UNMASK SENSOR
   170.5     INCREASE ALTITUDE       2 0 2 4                                                                  2  0  2  4

  FN. NUMBER: 54                                                            48
  FN. TITLE : UNMASK SENSOR                                                 TRACK TARGET                    ⑭             ⑮
   176.0     INCREASE ALTITUDE       2 0 2 4                              ⑬ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   176.5     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   177.0     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   177.5     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   178.0     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   178.5     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   179.0     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   179.5     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   180.0     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   180.5     INCREASE ALTITUDE       2 0 2 4                                ALIGN RETICLE       4 0 1 4   6  0  3  8   FVD         ACS 1
   181.0     CHECK LOS               1 0 2 4                                ALIGN RETICLE       4 0 1 4   5  0  3  8   ADC         ACS 2
   181.5     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   182.0     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   182.5     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   183.0     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   183.5     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   184.0     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   184.5     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   185.0     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
   185.5     CHECK LOS               1 0 2 4                                TRACK TARGET        4 0 3 4   5  0  5  8   ADC         AC  3
```

1. SEGMENT NUMBER. For convenience, the segments have been numbered from one through 29. The sequence of the segments is of no consequence in this analysis. The segments stand alone. The segment number is repeated at the top of each page through the printout. A segment always starts at the top of a page.

2. SEGMENT TITLE. The segment title always appears on the line directly beneath the segment number. Standardized segment titles appear on the segment summary worksheets, the summaries of concurrent and sequential workload demands, and the computer-generated segments presented on the printout.

3. FLIGHT, SUPPORT, MISSION, TOTAL, and SUBSYSTEMS. The headings FLIGHT, SUPPORT, and MISSION identify the columns that list flight control functions, support functions, and mission functions, respectively. The heading TOTAL identifies the column in which the workload estimates are summed across performance elements. The heading SUBSYSTEMS identifies the column in which subsystem codes are printed when overload conditions occur.

4. CUM. SECS., PERFORMANCE ELEMENTS, V A C P, and F S M. The heading CUM. SECS.--an abbreviation for cumulative seconds--identifies the column in which the timeline is presented. The timeline is cumulative from the beginning to the end of the segment. The timeline is explained further in paragraph 7 below.

The heading PERFORMANCE ELEMENTS is repeated three times on this line. The first of the three headings identifies the column that lists the performance elements that appear within flight control functions.

The second heading identifies the column that lists performance elements that appear within support functions. Performance elements that appear in mission functions are listed in the last of the three columns.

The letters V, A, C, and P are abbreviations for Visual, Auditory, Cognitive, and Psychomotor. Note that the set of four abbreviations is repeated four times on the same line. The first three sets identify columns that list estimates of workload components (visual, auditory, cognitive, and psychomotor) for the associated function class (flight control, support, or mission). The fourth set identifies the columns that list the sum of the workload values (summed across function classes).

The letters F, S, and M are abbreviations for flight control, support, and mission. They are headings for columns in which subsystem codes are listed when overload conditions occur. The three columns enable sorting the overload conditions into flight control, support or mission categories. See paragraph 15 below for additional information.

5. **FUNCTION NUMBER.** This data element identifies the number of the function being analyzed. The functions are numbered from one through 58. The numbers are merely identifiers; they do not indicate the order in which the functions are performed in the mission segment being analyzed. The function number(s) appear on all printout pages. The function number may indicate the start of the function, as in the case of the first page of each segment, or, as shown in Table 7, may indicate functions continuing from the previous page. The cumulative timeline is interrupted to present the function number and function title each time a new function starts in the middle of a page.

6. FUNCTION TITLE. Function titles are presented on the line directly beneath the function number. The function titles correspond to the titles on the respective function analysis worksheets presented in Appendix C.

7. TIME. The cumulative timeline is presented in half-second increments. The line presented as an example is at the 108.5-second point in the segment sequence.

8. PERFORMANCE ELEMENT. The circled number "8" in Table 7 is placed adjacent to the first performance element from a flight control function.

9. WORKLOAD ESTIMATES. At point 9 on the printout, the four columns of numbers represent the workload estimates for the associated performance element; in this case, Check Clearance. The values correspond to the estimates presented on the function analysis worksheet (see Appendix C).

10. TIMELINE. Although the program computes segment timelines in half-second increments, a line is printed only when a performance element changes or when an overload condition (see paragraph 14) is present. The time "130.0" indicates that a new performance element--Check Systems--started 130.0 seconds after the onset of the mission segment. The performance element, Check Clearance, starts at time 129.0, continues up to time 130.0, and then continues, accompanied by the performance element Check Systems, until time 131.5.

3.1

11. **PERFORMANCE ELEMENT.** The performance element, Adjust Power, is the first example in Table 7 of a performance element from a support function.

12. **TOTAL WORKLOAD.** Whenever two or three performance elements appear on the same line, the workload estimates are summed and presented in the total column. In this example, the cognitive value "2" for the Check Clearance performance element is added to the cognitive value "1" for the Adjust Power performance element, resulting in a value of "3" for the total estimate of the cognitive workload component.

13. **PERFORMANCE ELEMENT.** The performance element, Align Reticle, is the first example in Table 7 of a performance element from a mission function.

14. **TOTAL WORKLOAD INDICATING AN OVERLOAD CONDITION.** As stated above, the workload estimates from concurrent performance elements are summed and presented in the TOTAL column. In this example, the psychomotor value "4" for the performance element, Increase Altitude, is added to the psychomotor value "4" for the performance element, Align Reticle, resulting in a value of "8" for the total estimate of the psychomotor workload component. Any value of 8 or higher in the total workload columns is considered an overload condition.

15. **SUBSYSTEM IDENTIFIERS.** Whenever an overload condition occurs (as described in paragraph 14), identifier codes for the subsystems associated with the performance elements are listed on the printout. The subsystem identifier codes are presented in Table 6.

An Illustrative Example

The printout enables rapid identification of mission conditions likely to result in pilot overload and of candidate subsystems for automation. The presence of subsystem identifier codes on a timeline indicates that an overload condition exists at that point in time. The other data elements on the printout identify the workload components (V, A, C, P) that contribute to the overload, and the performance elements and functions within which the overload condition occurs.

Consider as an example the two subsystem codes FVD and ACS adjacent to the number 15 in Table 7. These two codes signal the presence of an overload condition. This is confirmed by the number 8 in the psychomotor column for the total workload. The code FVD indicates that the overload condition is associated with the subsystem "flight controls, visual scene, display"; the code ACS indicates that the overload is also associated with the subsystem "acquisition sensor controls/sight." (See Table 6 for a complete listing of subsystem identifier codes.) The code FVD is located in the "F" (flight control) column, and the code ACS is located in the "M" (mission) column. The location of the codes indicates that the overload is associated with a flight control function and a mission function. The associated performance elements are: Increase Altitude and Align Reticle. The performance element Increase Altitude is associated with the mission function Unmask Sensor (FN No. 54); the performance element Align Reticle is associated with the mission function Track Target. Thus, it can be seen that the pilot is increasing altitude, using the flight controls and the visual scene to unmask the aircraft; he is simultaneously manipulating the acquisition sensor controls to align the sight reticle, preparatory to tracking a target. The combined psychomotor workload demands from the flight controls and the acquisition sensor sight control constitute a probable psychomotor overload. The two subsystems, flight controls and acquisition sensor sight controls are candidates for automation.

Two-Crewmember Configuration

The basic printout format for the one-crewmember analysis was retained for the two-crewmember analysis. However, the 132-column limitation necessitated development of separate pilot and copilot printouts. The print programs were developed so that separate pilot and copilot printout pages can be placed side by side to depict concurrent timelines throughout the segment. Table 8 is a sample page from the pilot printout. Table 9 is a sample page from the copilot printout.

The selected printout pages are again from the segment depicted in Table 2, Table 5, and Table 7, Engagement, Air-to-Air From Masked Position. Note that the timelines are concurrent in the two tables. They both start at 112.0 seconds and end at 254.5 seconds. The timeline in Table 7, running from 108.5 to 185.5 is encompassed by the timeline in Tables 8 and 9, enabling comparisons between the one- and two-crewmember analyses.

Note that the pilot printout lists only performance elements from flight control and support functions. There are no instances in the

TABLE 8

SAMPLE PRINTOUT FROM THE TWO-CREWMEMBER ANALYSIS--PILOT

SEGMENT NUMBER: 25
SEGMENT TITLE : ENGAGEMENT, AIR TO AIR, FROM MASKED POSITION

CUM. SECS.	FLIGHT PERFORMANCE ELEMENTS	V A C P	SUPPORT PERFORMANCE ELEMENTS	V A C P	MISSION PERFORMANCE ELEMENTS	V A C P	TOTAL V A C P	SUBSYSTEMS F S M
FN. NUMBER: 25								
FN. TITLE : HOVER MASKED								
112.0	CHECK CLEARANCE	1 0 2 0					1 0 2 0	
114.5	CONTROL DRIFT	2 0 1 4					2 0 1 4	
133.3	CHECK CLEARANCE	1 0 2 0					1 0 2 0	
136.0	CONTROL DRIFT	2 0 1 4					2 0 1 4	
FN. NUMBER: 25			6					
FN. TITLE : HOVER MASKED			CHECK A/C SYSTEMS (PWR CHG)					
143.5	CONTROL DRIFT	2 0 1 4	ADJUST POWER	0 0 1 0			2 0 2 4	
144.5	CHECK CLEARANCE	1 0 2 0	CHECK SYSTEMS	5 0 2 0			6 0 4 0	
147.0	CONTROL HEADING	2 0 1 4	CHECK SYSTEMS	5 0 2 0			7 0 3 4	
FN. NUMBER: 25								
FN. TITLE : HOVER MASKED								
155.0	CHECK ALTITUDE	2 0 1 4					2 0 1 4	
FN. NUMBER: 54								
FN. TITLE : UNMASK SENSOR								
170.5	INCREASE ALTITUDE	2 0 2 4					2 0 2 4	
FN. NUMBER: 54								
FN. TITLE : UNMASK SENSOR								
176.0	INCREASE ALTITUDE	2 0 2 4					2 0 2 4	
181.0	STABILIZE AIRCRAFT	2 0 1 4					2 0 1 4	
181.5	STABILIZE AIRCRAFT	2 0 1 4					2 0 1 4	
FN. NUMBER: 54								
FN. TITLE : UNMASK SENSOR								
221.0	STABILIZE AIRCRAFT	2 0 1 4					2 0 1 4	
FN. NUMBER: 3								
FN. TITLE : ALIGN HEADING ON TGT BEARING								
221.5	ADJUST HEADING	4 0 5 4					4 0 5 4	
227.0	ADJUST HEADING	4 0 5 4					4 0 5 4	
228.5	ADJUST HEADING	4 0 5 4					4 0 5 4	
234.0	ADJUST HEADING	4 0 5 4					4 0 5 4	
251.0	STABILIZE AIRCRAFT	2 0 1 4					2 0 1 4	
251.5	ADJUST HEADING	4 0 5 4					4 0 5 4	
252.0	STABILIZE AIRCRAFT	2 0 1 4					2 0 1 4	
FN. NUMBER: 3								
FN. TITLE : ALIGN HEADING ON TGT BEARING								
254.5	STABILIZE AIRCRAFT	2 0 1 4					2 0 1 4	

TABLE 9

SAMPLE PRINTOUT FROM THE TWO-CREWMEMBER ANALYSIS--COPILOT

SEGMENT NUMBER: 25
SEGMENT TITLE : ENGAGEMENT, AIR TO AIR, FROM MASKED POSITION

	FLIGHT		SUPPORT		MISSION		TOTAL	SUBSYSTEMS
CUM. SECS.	PERFORMANCE ELEMENTS	V A C P	PERFORMANCE ELEMENTS	V A C P	PERFORMANCE ELEMENTS	V A C P	V A C P	F S M
FN. NUMBER: 66 FN. TITLE : STANDBY								
112.0							0 0 0 0	
114.5							0 0 0 0	
133.3							0 0 0 0	
136.0							0 0 0 0	
FN. NUMBER: 66 FN. TITLE : STANDBY								
143.5							0 0 0 0	
144.5							0 0 0 0	
147.0							0 0 0 0	
FN. NUMBER: 66 FN. TITLE : STANDBY								
155.0							0 0 0 0	
FN. NUMBER: 54 FN. TITLE : UNMASK SENSOR								
170.5	CHECK LOS	1 0 2 4					1 0 2 4	
FN. NUMBER: 60 FN. TITLE : STANDBY					48 TRACK TARGET			
176.0					ALIGN RETICLE	4 0 1 4	4 0 1 4	
181.0					ALIGN RETICLE	4 0 1 4	4 0 1 4	
181.5					TRACK TARGET	4 0 3 4	4 0 3 4	
FN. NUMBER: 60 FN. TITLE : STANDBY								
221.0							0 0 0 0	
FN. NUMBER: 60 FN. TITLE : STANDBY			20 ESTIMATE RANGE, UNAIDED					
221.5			ALIGN RETICLE	4 0 1 4			4 0 1 4	
227.0			SELECT FOV	1 0 1 1			1 0 1 1	
228.5			NOTE DIMENSIONS	6 0 6 4			6 0 6 4	
234.0			ESTIMATE RANGE	0 0 7 0			0 0 7 0	
251.0			ESTIMATE RANGE	0 0 7 0			0 0 7 0	
251.5			ESTIMATE RANGE	0 0 7 0			0 0 7 0	
252.0			ESTIMATE RANGE	0 0 7 0			0 0 7 0	
FN. NUMBER: 60 FN. TITLE : STANDBY					36 PREPARE WEAPON, FIRE & FORGET			
254.5					SELECT WEAPON	5 0 3 1	5 0 3 1	

entire two-crewmember analysis when the pilot performs a mission function. However, the copilot printout lists performance elements from flight control, support, and mission functions. A function entitled "Standby" was created to indicate timelines in the flight control column when the copilot is idle. The subheading explanations in numbered paragraphs 1 through 15 (above) apply to the subheadings in both the pilot and copilot printouts.

WORKLOAD TABULATIONS

For individuals who must make final decisions about the LHX design, there is no substitute for a careful study of the printouts generated by the computer analysis. However, data tabulations provide insights that are difficult to gain through study of the printouts alone. Consideration of a host of tabulation methods led project personnel to conclude that there is no single method that adequately conveys the full range of findings. Hence, a decision was made to present tabulations for four different, but related, indexes of the extent of operator overload:

- overload conditions,
- overloads,
- overload density, and
- subsystem overloads.

Definitions of these indexes and descriptions of the methods to count them are presented below, along with the resulting data.

Frequency of Overload Conditions

By definition, an overload condition is a situation in which some form of operator overload (one or more "8"s in the TOTAL column) is present. Simple counts of the overload conditions encountered during a mission segment provide a useful index of the presence and magnitude of a workload problem for that mission segment. A comparison of overload-condition counts for different mission segments provides a rough notion of the mission segments for which the workload problem is most severe. Before presenting data on overload conditions, it is necessary to describe the rules adhered to in counting the frequency of overload conditions.

It was concluded that it would be misleading to merely count the number of one-half-second timelines in which some form of overload is present; in other words, frequency and duration would be confounded. Such a count would reflect both the frequency and duration of overload conditions. For instance, a count of 50 would reflect either (a) a single overload condition that persists for 25 seconds (50 lines), or (b) five different overload conditions that last five seconds (10 lines) each. It was concluded that a more meaningful index is a count of only the frequency of overload conditions. The rules adhered to in counting overload conditions are as follows:

- Beginning at the start of a mission segment, an overload condition is counted on the first instance in which a value of "8" or higher is present in the TOTAL columns of the printout.
- Thereafter, another overload condition is counted each time there is one or more values of "8" or higher in the TOTAL columns <u>and</u> there is a change (from the previous overload condition) in (a) the verb or object of either a support or mission performance element, (b) the numerical values in the TOTAL columns, or (c) the subsystem identifier.

In short, an overload condition is counted any time a new type of overload is encountered in the TOTAL columns of the printout.

The frequencies of overload conditions for the one-crewmember and the two-crewmember configuration are shown in Table 10. Table 10 shows both (a) frequencies by mission segment, and (b) frequencies summed across mission segments. First compare total overload conditions for the one-crewmember and the two-crewmember configurations. As would be expected, the total overload conditions for the one-crewmember configuration (263 overload conditions) is far greater than for the two-crewmember configuration (43 overload conditions). This result indicates that, with no automation, operator overload is likely to be a far more severe problem for the one-crewmember configuration than the two-crewmember configuration.

Next, examine the overload conditions, by mission segment, for the one-crewmember configuration. It is clear that the operator overload problem is not unique to any one or small number of mission segments. There is no mission segment that has fewer than two overload conditions; there is one mission segment (Segment 5) during which 21 overload conditions occur. About 50% of the mission segments have 10 or more overload conditions. Furthermore, high frequencies of overload conditions tend to occur during mission segments in which the consequences of operator overload is most severe--with respect to crew safety and mission success.

The dramatic reduction from 263 to 43 overload conditions in the two-crewmember analysis is evident when examining the overload conditions by mission segment. Overload conditions are eliminated completely in 14 segments, by the addition of a second crewmember.

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TABLE 10

FREQUENCY OF OVERLOAD CONDITIONS BY MISSION SEGMENT: ONE-CREWMEMBER AND TWO-CREWMEMBER CONFIGURATIONS WITH NO AUTOMATION

SEGMENT NUMBER	TITLE	NUMBER OF OVERLOAD CONDITIONS	
		ONE-CREW-MEMBER	TWO-CREW-MEMBERS
	RECONNAISSANCE PHASE		
1	Bomb Damage Assessment	5	0
2	Evade Radar Lock-On	3	1
3	Reconnaissance, General	14	3
4	Record Sightings	10	2
5	Tactical Movement	21	3
6	Transmit Report, Digital	4	0
	TARGET SERVICE, GROUND		
7	Acquisition, Auto Search	12	3
8	Acquisition, From Laser Cuein	2	1
9	Adjustments, Area Weapons, Digital	4	1
10	Adjustments, Area Weapons, Voice	3	1
11	Designate for PCM	12	7
12	Engagement, Air-to-Ground, Autonomous, LOAL	15	1
13	Engagement, Ground Target, Autonomous, LOBL	18	5
14	Engagement, Ground Target, Remote Designation	8	0
15	Engagement, Soft Targets, Cannon Fire, Hover	7	0
16	Engagement, Soft Targets, FFAR, Direct	8	0
17	Handoff, Ground Target, Digital	5	0
18	Handoff, Ground Target, Voice	7	0
19	Handoff Target, Laser Cueing	5	0
20	Holding Checks	11	0
21	Overwatch	11	0
22	Receive Handoff, Voice	2	0
23	Team Coordination	11	3
	TARGET SERVICE, AIR-TO-AIR		
24	Acquisition, Free Search	19	7
25	Engagement Air-to-Air From Masked Position	14	0
26	Engagement Air-to-Air, Running Fire, Cannon	3	0
27	Engagement Air-to-Air, Running Fire, Missile	4	0
28	Handoff Aerial Threat, Voice	12	2
29	Receive Handoff, Voice	13	3
	TOTAL OVERLOAD CONDITIONS	263	43

Mission segment 25, Engagement, Air-to-Air From Masked Position, with 14 overload conditions in the one-crewmember analysis, has no overload conditions in the two-crewmember analysis. Other high workload segments in the one-crewmember analysis with overload conditions reduced to zero in the two-crewmember analysis include: (a) Segment 20, Holding Checks, and (b) Segment 21, Overwatch.

An important result from the two-crewmember analysis is that 40 of the 43 overload conditions are encountered by the copilot. This result is explained by the assignment of flight control functions to the pilot and support and mission functions to the copilot.

Frequency of Overloads

It will be recalled that the TOTAL column on the printouts has four sub-columns: one for visual (V), one for auditory (A), one for cognitive (C), and one for psychomotor (P). The four columns, heretofore termed "workload components," contain numbers that are the sum of workload component ratings for all performance elements being performed concurrently. A value of "8" or higher in any one of the four workload component columns indicates the presence of an "overload" for the associated workload component. By definition, at least one overload is present during every overload condition; and, in principle, as many as four overloads can be present during a single overload condition.

A tabulation of overloads by workload components provides diagnostic information about the causes of overload conditions. Specifically, such tabulations identify the type and number of overloads that contribute to an overload condition. Furthermore, the number of overloads per overload condition provides a crude index of the severity of the workload problem. For instance, it seems reasonable to assume that three overloads per overload condition would indicate a more severe workload problem than one overload per overload condition.

Table 11 shows the frequency of overloads by workload component and by mission segment. Overloads for the one-crewmember configuration and the two-crewmember configuration are shown separately. The columns in Table 11 labeled OVERLOADS PER CONDITION show the average number of overloads per overload condition. The numbers in these columns were derived by simply dividing total overloads for a mission segment (Table 11) by total overload conditions for the same mission segment (Table 10). The mission segment numbers and titles shown in Table 11 are the same as those shown in Table 10. Total overloads, summed across mission segments are shown at the bottom of each column.

First, consider overloads for the one-crewmember configuration. The overload totals at the bottom of Table 11 show that overloads are clearly not distributed equally over the four workload components. Not a single auditory overload was revealed by the analysis. The analysis revealed nearly 1.5 more visual overloads (79) than cognitive overloads (54) and revealed more than 2.5 times as many psychomotor overloads (205) as visual overloads (79). The total number of overloads summed across workload components is 338. Dividing the total number of overloads (338) by the total number of overload conditions (263) results in an average of 1.3 overloads per overload condition.

TABLE 11

FREQUENCY OF OVERLOADS BY MISSION SEGMENT AND WORKLOAD COMPONENT: ONE-CREWMEMBER AND TWO-CREWMEMBER CONFIGURATIONS WITH NO AUTOMATION

MISSION SEGMENT		NUMBER OF OVERLOADS									
		ONE-CREWMEMBER ANALYSIS					TWO-CREWMEMBER ANALYSIS				
NUMBER	TITLE	V	A	C	P	OVERLOADS PER CONDITION	V	A	C	P	OVERLOADS PER CONDITION
	RECONNAISSANCE PHASE										
1	Bomb Damage Assessment	4	-	2	4	2.0	-	-	-	-	0
2	Evade Radar Lock-On	2	-	3	-	1.7	-	-	1	-	1
3	Reconnaissance, General	4	-	-	12	1.1	2	-	2	2	2.0
4	Record Sightings	6	-	5	5	1.6	1	-	1	-	1.0
5	Tactical Movement	-	-	2	21	1.1	-	-	-	3	1.0
6	Transmit Report, Digital	-	-	1	3	1.0	-	-	-	-	0
	TARGET SERVICE, GROUND										
7	Acquisition, Auto Search	5	-	2	7	1.2	1	-	1	1	1.0
8	Acquisition, From Laser Cueing	-	-	-	2	1.0	-	-	-	1	1.0
9	Adjustments, Area Weapons, Digital	-	-	-	4	1.0	-	-	-	1	1.0
10	Adjustments, Area Weapons, Voice	-	-	-	3	1.0	-	-	-	1	1.0
11	Designate for PGM	9	-	3	12	2.0	7	-	-	-	1.0
12	Engagement, Air-to-Ground Autonomous, LOAL	8	-	3	11	1.5	-	-	1	-	1.0
13	Engagement, Ground Target Autonomous, LOBL	11	-	4	13	1.6	3	-	2	2	1.6
14	Engagement, Ground Target, Remote Designation	3	-	2	5	1.2	-	-	-	-	0
15	Engagement, Soft Targets, Cannon Fire, Hover	2	-	1	5	1.1	-	-	-	-	0
16	Engagement, Soft Targets, FFAR, Direct	1	-	2	7	1.2	-	-	-	-	0
17	Handoff, Ground Target, Digital	-	-	1	4	1.0	-	-	-	-	0
18	Handoff, Ground Target, Voice	-	-	-	7	1.0	-	-	-	-	0
19	Handoff Target, Laser Cueing	-	-	-	5	1.0	-	-	-	-	0
20	Holding Checks	6	-	5	1	1.1	-	-	-	-	0
21	Overwatch	1	-	1	10	1.1	-	-	-	-	0
22	Receive Handoff, Voice	-	-	-	2	1.0	-	-	-	-	0
23	Team Coordination	1	-	4	6	1.0	1	-	1	1	1.0
	TARGET SERVICE, AIR-TO-AIR										
24	Acquisition, Free Search	3	-	6	17	1.4	2	-	5	3	1.4
25	Engagement Air-to-Air From Masked Position	3	-	3	11	1.2	-	-	-	-	0
26	Engagement Air-to-Air, Running Fire, Cannon	2	-	-	1	1.0	-	-	-	-	0
27	Engagement Air-to-Air, Running Fire, Missile	4	-	1	1	1.5	-	-	-	-	0
28	Handoff Aerial Threat, Voice	2	-	2	11	1.2	2	-	1	-	1.5
29	Receive Handoff, Voice	2	-	1	13	1.2	2	-	2	-	1.3
	TOTAL OVERLOADS	79	-	54	205	1.3	24	-	17	15	1.3

An examination of overloads and overloads per condition by mission segment reveals the following important observations:

- Psychomotor overloads are pervasive. There is only one mission segment for which at least one psychomotor overload is not present. Ten or more psychomotor overloads are present for more than one-third of the mission segments; one mission segment has 21 psychomotor overloads.
- At least one visual overload is present for 20 of the 29 mission segments. There are five mission segments that have six or more visual overloads; one mission segment (Segment 13) has 11 visual overloads.
- Although cognitive overloads are less numerous than visual overloads, at least one cognitive overload is present for 21 of the 29 mission segments. The number of cognitive overloads per mission segment is less than for visual overloads and psychomotor overloads. For instance, there are only three mission segments for which cognitive overloads exceed four (Segments 4, 20, and 24).
- The number of overloads per overload condition varies from a value of 1.0 to a value of 2.0. It is worthwhile to note that the value of overloads per overload condition is positively related to total overloads--the larger the number of overloads, the larger the number of overloads per overload condition. This finding has important implications for attempts to assess the magnitude of the workload problem.

Now examine the overloads for the two-crewmember configuration. The overload totals at the bottom of Table 11 show that overloads are more equally distributed over the three workload components, visual, cognitive, and psychomotor, than in the one-crewmember analysis. Visual overloads have been reduced from 79 to 24 (70%); cognitive overloads have been reduced from 54 to 17 (69%), and psychomotor overloads have been reduced from 205 to 15 (93%). The total number of overloads summed across workload components has been reduced from 338 to 56 (83%). Dividing the total number of overloads (56) by the total number of overload conditions (43) results in an average of 1.3 overloads per overload condition.

Again, an examination of overloads and overloads per condition by mission segment reveals important observations:

- Psychomotor overloads are no longer pervasive. They occur only in nine segments. In five of the nine segments, only one overload occurs. The greatest number of psychomotor overloads (3) occurs in Segment 5, Tactical Movement; Segment 13, Engagement, Ground Target Autonomous, LOBL; and Segment 24, Acquisition, Free Search. The large reduction in psychomotor workload is attributed to the assignment of the flight control functions to the pilot. Throughout the analysis, the pilot performs the flight control functions unencumbered by support and mission functions.
- Visual overloads are present in nine of the 29 segments. Seven visual overloads occur in Segment 11, Designate for PGM.
- Cognitive overloads occur in ten of the 29 segments. Five cognitive overloads occur in Segment 24, Acquisition, Free Search. No other segment has more than two cognitive overloads.
- The number of overloads per overload condition varies from a value of 1.0 to a value of 2.0. The 2.0 value occurs in Segment 3, Reconnaissance, General. Although the overload conditions in Segment 3 are reduced from 14 to 3, the overloads were reduced only from 16 to 6. Thus, the crude index provided by the number of overloads per overload condition indicates a more severe workload problem in Segment 3 with two crewmembers than with one crewmember. An increased severity of workload is also indicated in Segments 28 and 29.

Overload Density

Another crude measure of the severity of the workload problem is provided by tabulating the overload density within the various mission segments. Overload density in these analyses is defined as the percentage of total time during a segment that some form of overload is present. It is calculated by dividing the total number of timelines with overloads in the segment by the total number of timelines in the segment:

$$\frac{\text{Number of timelines with overloads}}{\text{Total number of timelines in the segment}}$$

The number of timelines with overloads are easily tabulated by counting each timeline in which a value of 8 or higher occurs in one or more of the total columns. Timelines without overloads are not printed unless a performance element changes, but the total number of timelines in the segment can be calculated by multiplying the total segment time by 2. Thus:

$$\text{Overload density} = \frac{\text{Number of timelines with overloads}}{\text{Segment time x 2}}$$

Table 12 presents the results of the overload density tabulation for the 29 mission segments in the one-crewmember analysis. Segment 20, Holding Checks, has the highest overload density, .679. Segment 6, Transmit Report, Digital also has a high overload density (.603). Segments with low overload density include Number 2, Evade Radar Lock-On (.023); Number 8, Acquisition from Laser Cueing (.022); Number 10, Adjustments, Area Weapons, Voice (.061); Number 15, Engagement, Soft Targets, Cannon Fire, Hover (.052); and Number 16 Engagement, Soft Target, FFAR Direct (.089).

Table 13 presents the results of the overload density tabulations for the 29 mission segments in the two-crewmember analysis. The overload density is presented for both the pilot and copilot. Pilot overload density is very low in the three segments (2, 3, and 23) where pilot overload conditions occur. The overload density for the copilot has been dramatically reduced in comparison with the overload density tabulations for the one-crewmember analysis. The values range from zero in the 15 segments without overloads to a maximum value of .17 in Segment 24, Acquisition, Free Search.

TABLE 12

OVERLOAD DENSITY--ONE-CREWMEMBER ANALYSIS

SEGMENT	TITLE	NUMBER OF TIMELINES WITH OVERLOADS ÷	TOTAL NUMBER OF TIMELINES =	OVERLOAD DENSITY
1	Bomb Damage Assessment	127	1013	.125
2	Evade Radar Lock-On	14	598	.023
3	Reconnaissance, General	340	935	.361
4	Record Sightings	111	790	.141
5	Tactical Movement	167	711	.235
6	Transmit Report, Digital	205	340	.603
7	Acquisition, Auto Search	114	707	.161
8	Acquisition, From Laser Cueing	22	417	.022
9	Adjustments, Area Weapons, Digital	79	777	.102
10	Adjustments, Area Weapons, Voice	49	803	.061
11	Designate for PGM	101	512	.197
12	Engagement, Air-to-Ground Target, Autonomous LOAL	127	643	.196
13	Engagement, Ground Target Autonomous LOBL	139	623	.223
14	Engagement, Ground Target, Remote Designation	100	922	.108
15	Engagement, Soft Targets, Cannon Fire, Hover	47	904	.052
16	Engagement, Soft Target, FFAR Direct	96	1075	.089
17	Handoff, Ground Target, Digital	75	751	.100
18	Handoff, Ground Target, Voice	190	918	.207
19	Handoff, Laser Cueing	102	517	.197
20	Holding Checks	231	340	.679
21	Overwatch	180	1107	.163
22	Receive Handoff, Voice	74	340	.218
23	Team Coordination	110	330	.333
24	Acquisition, Free Search	179	552	.324
25	Engagement, Air-to-Air, From Masked Position	256	747	.343
26	Engagement, Air-to-Air, Running Fire, Cannon	16	158	.101
27	Engagement, Air-to-Air, Running Fire Missile	24	146	.164
28	Handoff, Aerial Threat, Voice	161	932	.173
29	Receive Handoff, Voice	186	718	.259

TABLE 13

OVERLOAD DENSITY--TWO-CREWMEMBER ANALYSIS

SEGMENT	TITLE	NUMBER OF TIMELINES WITH OVERLOADS ÷		TOTAL NUMBER OF TIMELINES =	OVERLOAD DENSITY	
		PILOT	COPILOT		PILOT	COPILOT
1	Bomb Damage Assessment	0	0	1024	.00	.00
2	Evade Radar Lock-On	1	0	598	.00	.00
3	Reconnaissance, General	8	9	915	.01	.01
4	Record Sightings	0	15	790	.00	.02
5	Tactical Movement	0	43	711	.00	.06
6	Transmit Report, Digital	0	0	340	.00	.00
7	Acquisition, Auto Search	0	16	707	.00	.02
8	Acquisition, From Laser Cueing	0	11	427	.00	.03
9	Adjustments, Area Weapons, Digital	0	9	777	.00	.01
10	Adjustments, Area Weapons, Voice	0	11	803	.00	.01
11	Designate for PGM	0	70	532	.00	.13
12	Engagement, Air-to-Ground Target, Autonomous LOAL	0	11	674	.00	.02
13	Engagement, Ground Target Autonomous LOBL	0	40	623	.00	.06
14	Engagement, Ground Target, Remote Designation	0	0	922	.00	.00
15	Engagement, Soft Targets, Cannon Fire, Hover	0	0	897	.00	.00
16	Engagement, Soft Target, FFAR Direct	0	0	1075	.00	.00
17	Handoff, Ground Target, Digital	0	0	750	.00	.00
18	Handoff, Ground Target, Voice	0	0	919	.00	.00
19	Handoff, Laser Cueing	0	0	517	.00	.00
20	Holding Checks	0	0	340	.00	.00
21	Overwatch	0	0	1109	.00	.00
22	Receive Handoff, Voice	0	0	340	.00	.00
23	Team Coordination	10	28	333	.03	.08
24	Acquisition, Free Search	0	94	552	.00	.17
25	Engagement, Air-to-Air, From Masked Position	0	0	667	.00	.00
26	Engagement, Air-to-Air, Running Fire, Cannon	0	0	158	.00	.00
27	Engagement, Air-to-Air, Running Fire Missile	0	0	146	.00	.00
28	Handoff, Aerial Threat, Voice	0	21	932	.00	.02
29	Receive Handoff, Voice	0	25	718	.00	.03

Subsystem Overloads

The subsystem identifiers associated with the overload conditions provide a means of identifying potential benefits of automation. Each of the (79 + 54 + 205 =) 338 overloads identified in Table 11 are associated with as few as one and as many as three different subsystems. If the overload is caused by two performance elements being performed simultaneously, one or two subsystem identifiers are associated with the overload. If the overload is caused by three performance elements being performed simultaneously, one, two, or three subsystem identifiers are associated with the overload. The term subsystem overload is used to denote the association between an overload and a subsystem. Table 14 is a matrix that presents the number of subsystem overloads in each segment in the one-crewmember analysis. They have been counted and categorized using the 10 subsystem groupings presented in Table 6; the 10 subsystem groupings are presented across the top of Table 14. The 29 mission segments are presented vertically. Each cell in the matrix presents the total number of subsystem overloads found in the analysis for each of the 29 mission segments.

The tabulation summarized in Table 14 provides diagnostic information helpful for identifying (a) the subsystems associated with the overloads, and (b) another crude index for identifying the mission segments with the fewest workload problems. The totals at the bottom of Table 14 show that subsystem overloads occur in every subsystem grouping presented in Table 6. They are not uniformly distributed over the 10 subsystem groupings. The highest number of subsystem overloads, 74% of

TABLE 14

SUMMARY OF OVERLOADS BY SUBSYSTEMS AND MISSION SEGMENTS--ONE CREWMEMBER ANALYSIS

MISSION SEGMENT	AIRCRAFT SUBSYSTEMS										TOTAL	OVERLOADS PER CONDITION
	FLIGHT CONTROL	TARGET ACQUISITION	COMMUNICATIONS	DISPLAY	FIRE CONTROL	NAVIGATION	LIFE SUPPORT	PERSONAL EQUIPMENT COCKPIT ITEMS	AIRCRAFT SURVIVABILITY	VISUAL FIELD		
1	9	7	3							1	20	4.0
2	5			3					2		10	3.3
3	14	11	3	4		1				2	35	2.5
4	14	19				10					43	4.3
5	14	27		1		4				1	47	2.2
6	3		4							1	8	2.0
7	9	7	5			5				2	28	2.3
8	2	2									4	2.0
9	4	4									8	2.0
10	3	2						1			6	2.0
11	14	34	21								69	5.8
12	18	23		4	11					3	59	3.9
13	26	32		4	9					1	72	4.0
14	7	1	1		4			1		6	20	2.5
15	5	4			3	3		1			16	2.3
16	8	3			6			1		2	20	2.5
17	3	5	1							1	10	2.0
18	6	8									14	2.0
19	3	7									10	2.0
20	7	4		1			2	3		7	24	2.2
21	10	10								4	24	2.2
22	2	1						1			4	2.0
23	4	7	4	1		3				3	22	2.0
24	24	35	5	1						3	68	3.6
25	14	18			1					1	34	2.4
26	3	1			2						6	2.0
27	6				6						12	3.0
28	13	16	7							1	37	3.1
29	15	16	6					1			38	2.9
TOTAL	265	304	60	19	42	26	2	9	2	39	768	2.9

the total, are in the flight control and target acquisition subsystem categories. The communications subsystem contributes 13%, the fire control subsystem contributes five percent, and the navigation subsystem three percent. The remainder of the subsystem overloads are distributed over the display, personal equipment and cockpit items, life support, and aircraft survivability categories.

Note that the flight control subsystem is associated with subsystem overloads in every mission segment; the target acquisition subsystem is associated with subsystem overloads in all but three segments. The aircraft survivability subsystem is associated only with overloads in Segment 2, Evade Radar Lock-On. Likewise, the life support subsystem is associated only with subsystem overloads in Segment 20, Holding Checks.

The subsystem overload totals for each of the mission segments are presented in the right-hand column. Segment 13, Engagement, Ground Target, Autonomous LOBL, has the highest number of subsystem overloads (72). Five subsystems, flight control, target acquisition, displays, fire control, and visual field are associated with the 72 subsystem overloads. Segment 11, Designate for PGM, has the next highest number of subsystem overloads (69). Only three subsystems, flight control, target acquisition, and communications are associated with the 69 subsystem overloads.

The OVERLOADS PER CONDITION column in Table 14 presents an index computed for each mission segment by dividing the total number of subsystem overloads by the total number of overload conditions (as reported in Table 10). An index number of "1" is the lowest number that can appear in this column. The presence of a number "1" indicates that for every overload condition reported in Table 10 (a) only one overload occurs (only one workload component is overloaded), and (b) only one subsystem grouping is associated with the overload. The highest number possible in the OVERLOADS PER CONDITION column is the index number "12." The number "12" indicates that for every overload condition reported in Table 10, (a) four overloads occur (all four workload components are overloaded), and (b) three subsystems (one from each of three concurrent performance elements) are associated with each of the overloads.

The values in the OVERLOADS PER CONDITION column range from a high of 5.8 to a low of 2.0. The highest value, 5.8, is for Segment 11, Designate for PGM. The 5.8 index value indicates that each overload condition is comprised of multiple overloads and that multiple subsystems are associated with the overloads. Thus, Segment 11 is identified as a segment with severe workload problems. In contrast, ten segments have 2.0 OVERLOADS PER CONDITION and can be considered the least severe from a workload standpoint, using this diagnostic index.

Table 15 presents the tabulation of subsystem overloads in the two-crewmember analysis. In contrast to the one-crewmember analysis, subsystem overloads occur only in six subsystem groupings. The highest number of subsystem overloads, 57% of the total, are in the target acquisition category. The communications subsystem contributes 18%, the display subsystem contributes three percent, the fire control subsystem contributes two percent, and the navigation subsystem five percent.

TABLE 15

SUMMARY OF OVERLOADS BY SUBSYSTEMS AND MISSION SEGMENTS--TWO-CREWMEMBER ANALYSIS

	AIRCRAFT SUBSYSTEMS											
MISSION SEGMENT	FLIGHT CONTROL	TARGET ACQUISITION	COMMUNICA-TIONS	DISPLAY	FIRE CONTROL	NAVIGA-TION	LIFE SUPPORT	PERSONAL EQUIPMENT COCKPIT ITEMS	AIRCRAFT SURVIVABILITY	VISUAL FIELD	TOTAL	OVERLOADS PER CONDITION
1												0
2				1		1					2	2
3		5		1		1				5	12	4
4		2				2					4	2
5		5								1	6	2
6												0
7		2	2							2	6	2
8		2									2	2
9		2									2	2
10		2									2	2
11		7	7								14	2
12		1			1						2	2
13		13			1						14	2.8
14												0
15												0
16												0
17												0
18												0
19												0
20												0
21												0
22												0
23		1	1	1		1				2	6	2
24		17	2							1	20	2.9
25												0
26												0
27												0
28		3	3								6	3
29		4	4								8	2.7
TOTAL		66	19	3	2	5				11	106	2.4

Subsystem overloads in the flight control, life support, personal equipment cockpit items, and aircraft survivability categories present in the one-crewmember analysis are eliminated by including a second crewmember in the analysis.

The target acquisition subsystem is associated with subsystem overloads in 14 of the 15 mission segments with overloads. Thus, the target acquisition subsystem is heavily associated with subsystem overloads in both the one- and two-crewmember analyses. The fire control subsystem is associated only with overloads in Segments 12 and 13 (Engagement, Air-to-Ground, Autonomous, LOAL and Engagement, Ground Target, Autonomous, LOBL).

Mission Segment 24 (Acquisition, Free Search, Air-to-Air) has the highest number of subsystem overloads (20). Segment 11 (Designate for PGM) and Segment 13 (Engagement, Ground Target, Autonomous LOBL) each have 14 subsystem overloads. These three segments contribute 45% of the subsystem overloads in the two-crewmember analysis. The reduction of total subsystem overloads from 768 in the one-crewmember analysis to 106 in the two-crewmember analysis represents an 86% reduction in this crude diagnostic index.

Segment 24 (Acquisition, Free Search, Air-to-Air) and Segment 13 (Engagement, Ground Target, Autonomous LOBL) have 2.9 and 2.8 OVERLOADS PER CONDITION, respectively. These two segments are identified as the segments with severe workload problems for the copilot. Again, there are ten segments with OVERLOADS PER CONDITION values of 2.0.

REDUCING WORKLOAD THROUGH AUTOMATION--AN ANALYSIS

The computer model provides the capability to revise workload estimates at the performance element level of specificity. Changes are made directly in the performance element data file. This capability enables rapid evaluation of the effect of proposed automation options on operator workload. New estimates of workload are generated for performance elements associated with the automated subsystems. The computer printout for each analytic iteration shows the number and type of overload conditions that remain after the effects of the automation have been taken into account.

Prior to exercise of the model, a manual analysis was performed using results from the baseline configuration printouts to estimate the degree of automation that would be required to eliminate all overload conditions. The manual analysis was performed segment by segment, following the steps presented in Figure 1 and described below.

First, the overloads within each segment were categorized by subsystem. Then, the subsystem grouping with the largest number of overloads was examined. Automation options were identified for reducing overloads. The function analysis worksheets were revised with new workload estimates for each performance element affected by the automation. The new workload estimates were applied to the timelines on the printout to determine if the overload conditions were eliminated. Then the subsystem grouping with the next largest number of overloads was examined. The process was continued until either all overloads in the segment were eliminated or all possible automation options had been exhausted.

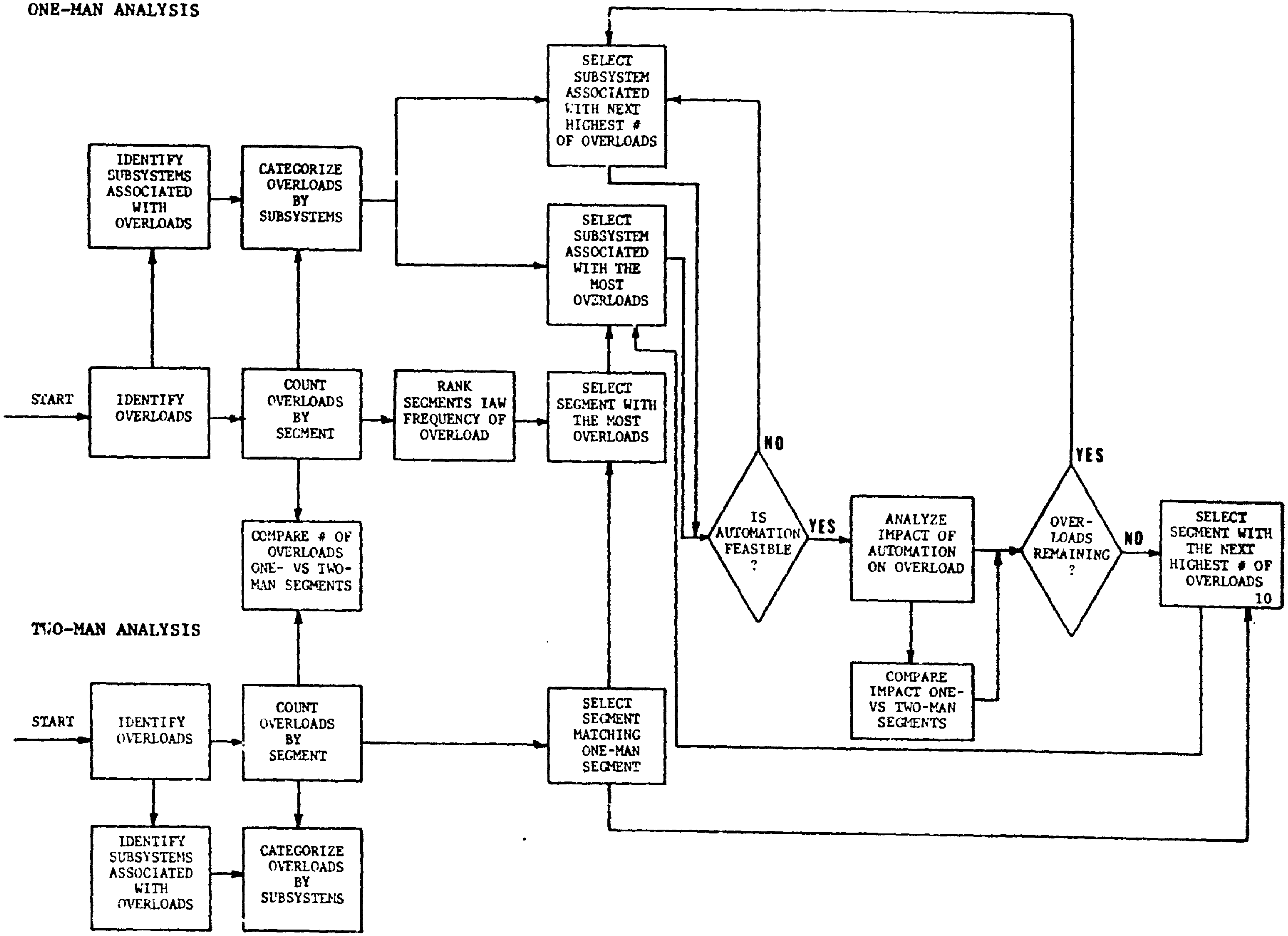

Figure 1. Flow diagram: Procedure for estimating automation required to eliminate overload conditions.

Table 16 is a matrix that summarizes the results of the manual analysis. Segment numbers are listed across the top of the matrix. Automation options required to reduce the overloads are listed in the left-hand column. The letter "P" is placed in a cell of the matrix when the corresponding automation option is required to eliminate one or more pilot overloads for the corresponding mission segment. The Ps in a column of the matrix show the number and type of automation options required to eliminate all overloads for the corresponding mission segment. The Ps in a row of the matrix show the mission segments for which overloads would be eliminated by the corresponding automation option.

Twenty-eight automation options were postulated during the manual analysis. The selected automation options eliminated all the overloads in the one-crewmember analysis except the following.

- Segment 1: Bomb Damage Assessment. From the 322.0 to the 337.0 timeline, the pilot is performing the flight control function "Unmask Sensor" and simultaneously performing the mission function "Survey Target Area." The performance elements contributing to the overloads are (a) "Stabilize Aircraft" and "Estimate Percentage of Coverage" and (b) "Stabilize Aircraft" and "Determine Percentage of Targets Disabled." A hover hold option eliminates the visual and psychomotor overloads in both of the above conditions, but the cognitive overload remains. The cognitive workload required to monitor a hover hold condition and simultaneously estimate coverage of the target area and percentage of targets disabled are not reducible through automation unless an automatic capability exists for recognizing enemy targets and discriminating between those disabled and operable.
- Segment 21: Holding Checks. There are two overloads in this segment not reducible by automation. In both cases, the pilot is performing the flight control function "Hover Masked." In the first overload, the pilot is also checking his life support equipment and in the second overload, he is checking personal equipment items in the cockpit. The cognitive workload demands required to monitor a hover hold condition and simultaneously

SEGMENT-BY-SEGMENT SUMMARY OF AUTOMATION OPTIONS REQUIRED TO REDUCE OVERLOAD CONDITIONS--ONE CREWMEMBER LHX MISSION ANALYSIS

	MISSION SEGMENT																												
AUTOMATION OPTIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
TARGET ACQUISITION																													
AUTOMATIC SEARCH				P	P																		P	P	P			P	P
AUTOMATIC TARGET DETECTION				P	P																		P	P	P			P	P
AUTOMATIC TARGET RECOGNITION				P																				P	P			P	P
AUTOMATIC TARGET PRIORITIZATION				P																				P	P			P	P
AUTOMATIC SIGHT ALIGNMENT				P	P						P	P	P				P	P	P				P	P	P	P		P	P
AUTOMATIC TARGET TRACKING											P	P	P					P	P		P			P	P			P	P
AUTOMATIC TARGET RECAPTURE																		P						P					
AUTOMATIC RANGE CALCULATION																								P	P				
FLIGHT CONTROL																													
HOVER HOLD FOR CONTROLLING HEADING, ALTITUDE, LOCATION	P		P	P		P	P	P	P	P			P	P	P	P		P	P	P	P	P			P			P	P
AUTOMATIC INCREASE ALTITUDE MODE DURING HOVER, VOICE COMMANDED	P		P	P			P	P	P	P				P	P	P		P			P								
AUTOMATIC DECREASE ALTITUDE MODE DURING HOVER, VOICE COMMANDED									P								P												
AUTOMATIC ALIGNMENT OF AIRCRAFT HEADING ON TARGET DURING HOVER (VOICE COMMANDED)													P																
COMMUNICATIONS																													
VOICE PLAYBACK FOR MESSAGE DISPLAY											P																		
AUTOMATIC AUTHENTICATION OF MESSAGE						P											P						P						
CHANNEL SELECTION BY VOICE COMMAND							P																						
VOICE RECORDER FOR MESSAGE ENTRY DURING LOW WORKLOAD INTERVALS	P						P																						
AUTOMATIC TRANSMISSION FROM RECORDER UPON VOICE COMMAND							P																P						
FIRE CONTROL																													
AUTOMATIC WEAPON SELECTION															P											P	P		
AUTOMATIC VERIFICATION AIRCRAFT IS IN FIRING CONSTRAINTS												P	P	P		P											P		
AUTOMATIC WEAPON RELEASE												P																	
AUTOMATIC DE-ARMING OF WEAPON AFTER WEAPON RELEASE												P	P	P													P		
NAVIGATION																													
AUTOMATIC DISPLAY OF AIRCRAFT POSITION RELATIVE TO SELECTED WAYPOINTS				P																	P								
AUTOMATIC UPDATING OF POSITION				P										P															
DISPLAY																													
VOICE DISPLAYS FOR SYSTEM CHECKS			P																				P						
AIRCRAFT SURVIVABILITY																													
AUTOMATIC DIAGNOSIS AND VERIFICATION OF THREAT SIGNALS		P																											
AUTOMATIC STORAGE OF THREAT SOURCE LOCATIONS		P																											
AUTOMATIC ACTIVATION OF ELECTRONIC COUNTERMEASURES		P																											
PERSONAL EQUIPMENT, COCKPIT ITEMS																													
VOICE PRESENTATION OF CHECKLIST																					P								

perform each of the two checks is not reducible by automation. However, both of the checks can be delayed to coincide with less demanding flight control performance elements.

Table 16 indicates that the majority of the overloads can be eliminated by providing automated flight control and target acquisition systems. Every segment except Number 2, Evade Radar Lock-On, and Number 27, Engagement, Air-to-Air, Running Fire, Cannon, require at least one automated target acquisition or automated flight control option. The option Hover Hold for Controlling Heading, Altitude, Location is required in 20 of the 29 mission segments, more than any other single option. The option Automatic Sight Alignment is required in 14 segments. The option Automatic Increase Altitude Mode During Hover Voice Commanded, is required in 12 segments and the option Automatic Target Tracking is required in ten segments.

A sufficient number of overload conditions occur during operation of the communications, fire control, navigation, display, and survivability subsystems to warrant automation if the LHX is to be designed for single-crewmember operation. Eight of the 28 automation options are required in one segment only. They are:

- automatic alignment of aircraft heading on target during hover (voice commanded),
- voice playback for message display,
- channel selection by voice command,
- automatic weapon release,
- automatic diagnosis and verification of threat signals,
- automatic storage of threat source locations,
- automatic activation of electronic countermeasures, and
- voice presentation of checklist.

Seven of the 28 automation options are required in two segments only. They are:

- automatic target recapture,
- automatic range calculation,
- automatic decrease altitude mode during hover, voice commanded,
- voice recorder for message entry during low workload intervals,
- automatic transmission from recorder upon voice command,
- automatic display of aircraft position relative to selected waypoints
- automatic updating of position.

An analysis comparable to the above was performed manually to determine now much automation will be required to eliminate all overloads in the two-crewmember LHX. The steps in the manual analysis were repeated and the results are depicted in Table 17. Again, the segment numbers are listed across the top of the matrix and the automation options required to reduce the overloads are listed in the left-hand column. A "P" is placed in a cell of the matrix when the corresponding automation option is required to eliminate pilot overloads in the corresponding mission segment. A "C" is placed in a cell of the matrix when the corresponding automation option is required to eliminate copilot overloads in the corresponding mission segment. The Ps and Cs in a column of the matrix show the number and type of automation options required to eliminate all overloads from the corresponding mission segment. The Ps and Cs in a row of the matrix show the mission segments for which overloads would be eliminated by the corresponding automation option.

TABLE 17

SEGMENT-BY-SEGMENT SUMMARY OF AUTOMATION OPTIONS REQUIRED TO REDUCE OVERLOAD CONDITIONS--TWO-CREWMEMBER LHX MISSION ANALYSIS

	MISSION SEGMENT																												
AUTOMATION OPTIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
TARGET ACQUISITION	*					*								*	*	*	*	*	*	*	*	*			*	*	*		
AUTOMATIC SEARCH			C		C		C	C	C	C														C					C
AUTOMATIC TARGET DETECTION			C		C			C	C	C														C					C
AUTOMATIC TARGET RECOGNITION			C		C																			C					C
AUTOMATIC SIGHT ALIGNMENT			C	C	C			C	C	C	C		C											C				C	C
AUTOMATIC TARGET TRACKING											C		C											C				C	C
AUTOMATIC TARGET RECAPTURE																								C				C	C
FIRE CONTROL																													
AUTOMATIC VERIFICATION AIRCRAFT IS IN FIRING CONSTRAINTS												C	C																
NAVIGATION																													
AUTOMATIC DISPLAY OF AIRCRAFT POSITION RELATIVE TO SELECTED WAYPOINTS				C			C																C						
DISPLAY																													
VOICE DISPLAYS FOR SYSTEM CHECKS			P																				P						
AIRCRAFT SURVIVABILITY																													
AUTOMATIC DIAGNOSIS AND VERIFICATION OF THREAT SIGNALS		P																											

*No overloads.

Ten automation options were postulated during the manual two-crewmember analysis. The selected automation options eliminated all of the overloads in the two-crewmember analysis. This contrasts markedly with the 28 automation options required to eliminate most of the overloads in the one-crewmember analysis.

Table 17 indicates that the majority of overloads can be eliminated by providing automated target acquisition systems. The option, Automatic Sight Alignment, is required in 11 of the 15 mission segments with overloads. The option, Automatic Search, is required in eight segments, and the option, Automatic Target Detection, is required in seven segments.

Overload conditions do occur during operation of the fire control and navigation subsystems in selected segments. However, the two-crewmember analysis indicates, in contrast to the one-crewmember analysis, that automation is not required in the flight control, communications, display, and aircraft survivability subsystems. Only one of the ten automation options, Automatic Diagnosis and Verification of Threat Signals, is required in one segment only.

DISCUSSION AND CONCLUSIONS

The LHX mission analyses have strengths and weaknesses that must be recognized as the results are evaluated for application to the LHX design decisions. This section presents some practical applications and discusses strengths and limitations of the methodology and models. Plans for future LHX mission analyses are presented. Finally, the results are interpreted and recommendations presented regarding the critical human factors question: Should the LHX be designed for one or two-crewmember operation?

PRACTICAL APPLICATIONS AND METHODOLOGICAL STRENGTHS

The mission analysis methodology, despite some weaknesses (presented below), provides a systematic means of predicting human operator workload in advance of system design. Predicting operator workload presents a challenging problem despite recent but inconclusive progress in developing methods for measuring workload. The rudimentary, non-validated methods described herein must be evaluated within that context. The methodology presents a beginning; refinements can occur as workload measurement research progresses.

Systematic prediction of workload provides an excellent foundation for human engineering design decisions during the advanced study or conceptual phase of system design. Basic decisions about what functions should be assigned to humans and what functions should be assigned to machines are made in these early studies and trade-off analyses. The model described above provides an excellent tool for addressing such issues.

The analyses described above are baseline. They were conducted by defining generic mission functions; no specific system design was attempted. The methodology allows for improvements in the analyses as the system definition proceeds. The estimates of workload can be refined as iterations of the analyses are performed in pace with the LHX system definition and development. Through successive iterations, the mission analysis can evolve into a task analysis with the workload and time estimates derived from system design parameters. In the meantime, the designers have been provided with systematically derived estimates of workload. Such estimates can drive design decisions. Estimates of the sensory demands provide information about display requirements. Estimates of the psychomotor requirements provide information relevant to control and switch design. Estimates of the cognitive complexity provide early information about where human factors design attention should be focused whatever crew station components are required.

There are several features in the mission analysis and the computer models designed to limit the estimation of excessive workload conditions. Therefore, the predictions of workload can be considered conservative. Features guarding against over prediction of workload include the following:

- Time estimates for performance elements are conservatively long. This provides more flexibility in the scheduling of the crew activities and minimizes overload conditions.
- Support functions are scheduled on the timeline to prevent high workload. To the extent possible, they are scheduled when no mission functions are being performed.

- The duration of flight control functions are extended as necessary to assure that all required support and mission performance elements are presented on the timeline. Thus, overload conditions associated with time stress are not predicted by the model.
- The establishment of the value "8" as the overload threshold overlooks the possibility that overload may exist at a lower value during concurrent performance elements. A concurrent visual "7," cognitive "7," and psychomotor "7" may constitute a more critical overload condition than the single value "8." Such concurrent conditions across workload components are not considered in the prediction of overload.
- Summing the workload component ratings to obtain the total concurrent workload is conservative. The real workload may be greater than the sum of the parts.
- The analysis does not take into consideration increases in workload associated with mission degradation due to visual obscuration (night, dust weather), malfunctioning subsystems, fatigue, and enemy action.

SOME LIMITATIONS AND RESEARCH ISSUES

The greatest weakness in the mission analysis stems from the subjective nature of the workload estimates. Assigning numbers to the estimates and processing them with a computer does not attenuate the subjectivity. The following paragraphs describe specific methodological limitations that must be recognized when interpreting the results of the analyses conducted to date.

The scales presented in Table 3 were developed during the original analysis (McCracken & Aldrich, 1984). The scale values indicate increasing complexity of the workload components. The analysts judged that the verbal descriptors denote increasing complexity corresponding to the scale values. McCracken and Aldrich assigned scale values , comparing the verb/object and workload descriptors on the functional analysis worksheets with the verbal designators in Table 3. The analysts reached consensus in their judgments. This consensus was reviewed by two subject matter experts. However, the scales have not been subjected to traditional reliability and validity studies. There has not been sufficient time to perform such studies in step with the LHX system milestones.

Another methodological weakness exists in the procedure for computing the total workload estimates on the summary of concurrent and sequential workload demand worksheets (see Table 5) and by the computer as described on page 40, numbered paragraph 12. The scales in Table 3 are ordinal at best. Summing the modality values to derive a total estimate is a questionable procedure. In fact, there is no evidence that compounding workload demands are additive. Most of us can recall circumstances when ever increasing workload seemed to be synergistic.

Another methodological weakness stems from the treatment of the various components of workload as separate, independent entities. It is doubtful that psychomotor workload exists independent of cognitive and visual workload. What happens to the sensory and/or cognitive workload if you attenuate the psychomotor workload associated with a particular performance element? The model assumes that the sensory and/or cognitive estimates are unchanged.

The analysts' decision to designate the total value of "8" as the overload threshold is another subjective aspect of the methodology. Expert opinion is the only basis for selecting "8" as the threshold for a predicted operator overload. Hence, the selection of the "8" can be questioned.

The time estimates assigned to the performance elements represent a consensus of the analysts. The times were reviewed by a highly experienced and current AH-1 aviator and also by a highly experienced and current aeroscout aviator. However, the time estimates require refinement through several iterations as the conceptual and subsequent design and development phases of the LHX ensue. The validation for the estimated times must await further system definition.

The accuracy of the time estimates are not as critical as they would be if the study objectives required identification of excessive workload caused by time pressure. In fact, as stated above, the function time estimates are conservatively long to increase the likelihood that all concurrent, competing demands are identified. During the reassembly of the functions in the summary of concurrent and sequential workload demands (Table 5) and in the decision rules (Appendices F and G), the times for the flight control functions were extended to allow concurrent support and mission functions to be completed. This resulted in some unrealistic timelines, from an operational point of view. An LHX would be extremely vulnerable in a battle area if the pilot hovered in an unmasked sensor mode of flight for 40 seconds. However, extending the unmask sensor timeline permitted identification of all the concurrent performance overloads likely to occur. The very real demands on the pilot as a function of time stress are not accounted for in the model.

All of the above limitations and weaknesses identify areas where research is needed before methods for predicting workload can advance.

In the meantime, the practical value of the analyses will be evaluated as future iterations are performed in step with LHX system development.

FUTURE LHX MISSION ANALYSES AND VALIDATION STUDIES

Additional mission analyses are required. As the LHX system definition progresses and specific design alternatives are considered, the computer models can be exercised to identify the best design for minimizing operator workload. Moreover, the models can be exercised to simulate performance degradation resulting from system malfunctions, visual obscuration, or enemy countermeasures. The evaluative analyses performed during systems definition can be used to assist in human engineering design decisions. They also can be used to provide early identification of emerging requirements for LHX aviator training.

The most suitable means of validating the workload analyses is through flight simulation. Workload estimates, performance times, incidents of overload, and the impact of subsystem automation can be evaluated by collecting empirical data during trials in a flight simulator. The mission analysis provides a scenario for flight simulation. The estimates of workload, performance times, and incidents of overload provide a host of hypotheses testable in flight simulation experiments.

Flight simulation can be used to refine the workload estimates and to measure performance times. Once subjects have participated in LHX flight simulation, subjective workload measures can be collected. Measuremen instruments, such as those developed for SWAT (Reid, Shingledecker, & Nygren, 1981) and the Modified Cooper Harper scale (Wierwille & Casali, 1983) can be administered. Results from these measurements can be compared with predictions of workload provided by the model. Such results can be used to improve the mission analysis methodology.

Flight simulation has become an essential design tool to be employed early in system development. The advanced development simulation studies being performed by the five contractors as they explore new concepts for Advanced Rotorcraft Technology Integration (ARTI) is a contemporary example with direct application to the LHX. Validation of the mission analysis can be performed concurrent with the use of flight simulation for design and development. Moreover, the computerized mission analysis can contribute to the conduct of flight simulation design studies.

CONCLUSIONS

Conclusions stated below are based solely on results from the computerized baseline mission analyses and the manual analyses of the effect of automation on workload in the one- and two-crewmember configurations. The effect of various automation options as determined by exercising the computer model will be presented in a future report.

The large number of overload conditions identified in the one-crewmember analysis leads to a conclusion that a high degree of automation will be required if a lone aviator is to fly and operate the LHX. Many of the overload conditions reported in Table 10 represent overloads impacting more than one modality at the same time. Providing the pilot with automation options to reduce the psychomotor workload will not suffice. Visual and cognitive overload conditions must also be accounted for.

The manual analysis of automation failed to eliminate all overload conditions during single-crewmember operation. The 28 automation options eliminate all overloads except two in Segment 1, Bomb Damage Assessment, and two in Segment 21, Holding Checks (see page 66). The Bomb Damage Assessment segment requires two crewmembers, one to fly the LHX and one to estimate the percentage of target area covered and the percentage of targets disabled. (The two overloads in Segment 21 occur during performance of cockpit checks. They can be delayed to coincide with less demanding flight control performance elements.) This analysis cannot support a decision to design the LHX for single aviator operation unless Bomb Damage Assessment is eliminated as a mission requirement.

Even then, support for a single-crewmember LHX would have to be qualified. The finding that the majority of the overload conditions are eliminated by the 28 automation options may encourage proponents of a single-crewmember LHX configuration. It is beyond the scope of this mission analysis to assess the technological risks associated with each of the 28 automation options. However, even if the automation options are within the state of the art, proponents must be concerned with their reliability in a battlefield environment. Malfunctions and failures of the automated subsystems will overload a single aviator. In such cases, the aviator will revert to manual operation and encounter the overload conditions identified in these analyses. Mission performance will be degraded.

In summary, the results of the analyses reported here do not support a decision to design a single seat LHX unless:

- Bomb Damage Assessment is eliminated as a mission requirement, and
- all 28 automation options are provided with extraordinarily high reliability.

Despite the reduction of overload conditions in the two-crewmember analysis, automation will be required to operate the LHX. As in the one-crewmember analysis, Table 10 reports overloads in the two-crewmember analysis impacting more than one modality at the same time. Visual, cognitive, and psychomotor overload conditions must be accounted for.

The analysis of automation required to eliminate all overload conditions leads to the conclusion that dual-crewmember operation is feasible across the full range of the LHX missions. The ten automation options eliminate overloads that have not been eliminated by dividing the workload among the two crewmembers.

In summary, there are several findings that indicate that the two-crewmember LHX is a preferred configuration.

- All overload conditions are eliminated by ten automation options.
- The pilot is overloaded only during three of the 29 mission segments, even without automation.
- Fourteen mission segments can be performed without overload and with no automation.
- Four subsystem categories (flight control, life support, personal equipment cockpit items, and aircraft survivability) require no automation.

These LHX mission analyses support the conclusions that (a) a two-crewmember configuration is preferred for the LHX, and (b) automation will be required so that LHX crews are not overloaded during critical mission segments.

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ANNEX R-V

VISUALLY COUPLED AIRBORNE SYSTEMS SIMULATOR (VCASS) LIGHT HELICOPTER FAMILY (LHX) COCKPIT SIMULATION

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Annex V to Appendix R

VISUALLY COUPLED AIRBORNE SYSTEMS SIMULATOR (VCASS)
LIGHT HELICOPTER FAMILY (LHX) COCKPIT SIMULATION

R-V-1. Reproduced on the following pages is a report describing work performed by the Visual Display Systems Branch, Human Engineering Division, Air Force Aerospace Medical Research Laboratory. It is reproduced here in its entirety for the convenience of those with sufficient interest.

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PREFACE

This report describes an effort performed by the Visual Display Systems Branch, Human Engineering Division, Air Force Aerospace Medical Research Laboratory (AFAMRL/HEA) under Project 7184, Man-Machine Integration Technology, Task 718411, Design Parameters for Visually Coupled Systems and Visual Display Systems, and Work Unit 71841145, Display Requirements for Tactical Night Systems. The authors wish to thank Captain Flint W. Hickman of the U.S. Army Aviation Center, Directorate of Combat Development, Fort Rucker AL, who provided the essential Army mission and procedures information needed to produce a viable simulation effort. Special thanks are also extended to Captain Loran A. Haworth, Captain Roy Schandorf, CW4 H. John Abreu, and CW2 Patrick Tate, all U.S. Army helicopter pilots (and subjects in this study) who gave so generously and enthusiastically of their time and experience to assure success of this project.

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1.0 INTRODUCTION/BACKGROUND.

This report summarizes the results of a preliminary experimental simulation of a helicopter attack mission using the Visually Coupled Airborne Systems Simulator (VCASS).

This effort grew out of the earlier "Technology Assessment Study: Virtual Panoramic Display for the LHX" (LHX = Light Helicopter Family), the results of which were presented to Army personnel 12 July 1984 at Wright-Patterson AFB. Since that Phase I study indicated that field-of-view (FOV) was an important variable for performance and pilot acceptance of a panoramic display, the Directorate of Combat Developments (DCD), Army Aviation Center, Ft. Rucker, AL requested that the Air Force Aerospace Medical Research Laboratory (AFAMRL) develop a preliminary (pre-Phase II) simulation of an LHX mission in which various FOV's could be flown by experienced Army helicoptor pilots. The primary purpose of this exercise was to provide hands-on experience with the VCASS simulator and develop some subjective "feel" for the effect of various FOV's on the ability to accomplish the mission.

2.0 DESCRIPTION OF VCASS SIMULATION.

The VCASS facility has been developed by the Visual Display Systems Branch of the Human Engineering Division within the AFAMRL at Wright-Patterson AFB, OH. A comprehensive description of the VCASS simulator, as functionally configured for the LHX, is contained in the report by Haas (1984). Briefly, VCASS provides a capability to present computer generated imagery on a helmet-mounted display (HMD) to each eye independently. Each ocular of the HMD optics can provide a FOV of up to 60 degrees vertical by 80 degrees horizontal, with up to 40 degrees overlap between the fields. Thus, the size of the FOV may be manipulated for experimental evaluation. The instantaneous orientation of the oculars (as controlled by head movement) is measured by a magnetic helmet tracker, allowing information displayed on the oculars to be translated relative to head movement so that the displayed images appear to be stable in space. In this way, a panorama of information is available to the operator as a function of head position. Neither the flight control characteristics (flight dynamics model) nor the terrain portrayal were developed beyond that demonstrated during the Phase I (Technology Assessment Study) effort, and this provided rigid constraints on the fidelity of both the flight control algorithms and the quality of the terrain representation. In spite of these limitations, the DCD Office felt that the virtual panoramic display (VPD) concepts that could be demonstrated in VCASS were powerful enough to justify pilot familiarization trials from which important information could be gleaned for tradeoff analysis applications. Of special interest was the concern for the instantaneous FOV of the helmet-mounted display which would render the outside world and cockpit presentations. In addition, a familiarization study would provide an opportunity to develop and test data collection software and would provide an assessment of the VCASS development effort in terms of its current ability to meet the demands of simulation schedules for applications research. Thus, VCASS improvements could be identified that would lead to higher fidelity simulations for exploratory and engineering design investigations.

3.0 VIRTUAL COCKPIT DISPLAY FORMATS.

The virtual cockpit, as it was employed in the present simulation, is depicted in Figure 1. Missile selection, electronic countermeasures aircraft survivability equipment (ECM/ASE) activation, and target designation could all be executed by positioning the "cross hairs" reticle over the intended object. Reticle position is measured by the VCASS helmet mounted sight (HMS) system, and is boresighted by the pilot prior to flight. The virtual cockpit also included a heading tape, flight director information, altitude, airspeed, missiles, and ECM/ASE status, as shown. (See Haas, 1984, for a detailed description of the operation and behavior of these display elements under aircraft and head movements.) The diamond (on the horizontal bar next to the reticle in this picture) provides a steering command, while the adjacent numeric readout provides the flight vector to the target. Airborne and ground threats (in their programmed x, y and z coordinate positions) are viewable in the out-the-window scene, provided they are close enough and the pilot has them within his FOV. Similarly, tracer rounds from either the LHX or a simulated Soviet Hind helicopter, as well as missile launches and hit bursts, are displayed. Figure 2 shows the total VPD concept, which includes both the virtual cockpit and the rudimentary terrain depiction. Solid and dashed lines represent ground and water features, respectively.

4.0 SIMULATION CONSIDERATIONS.

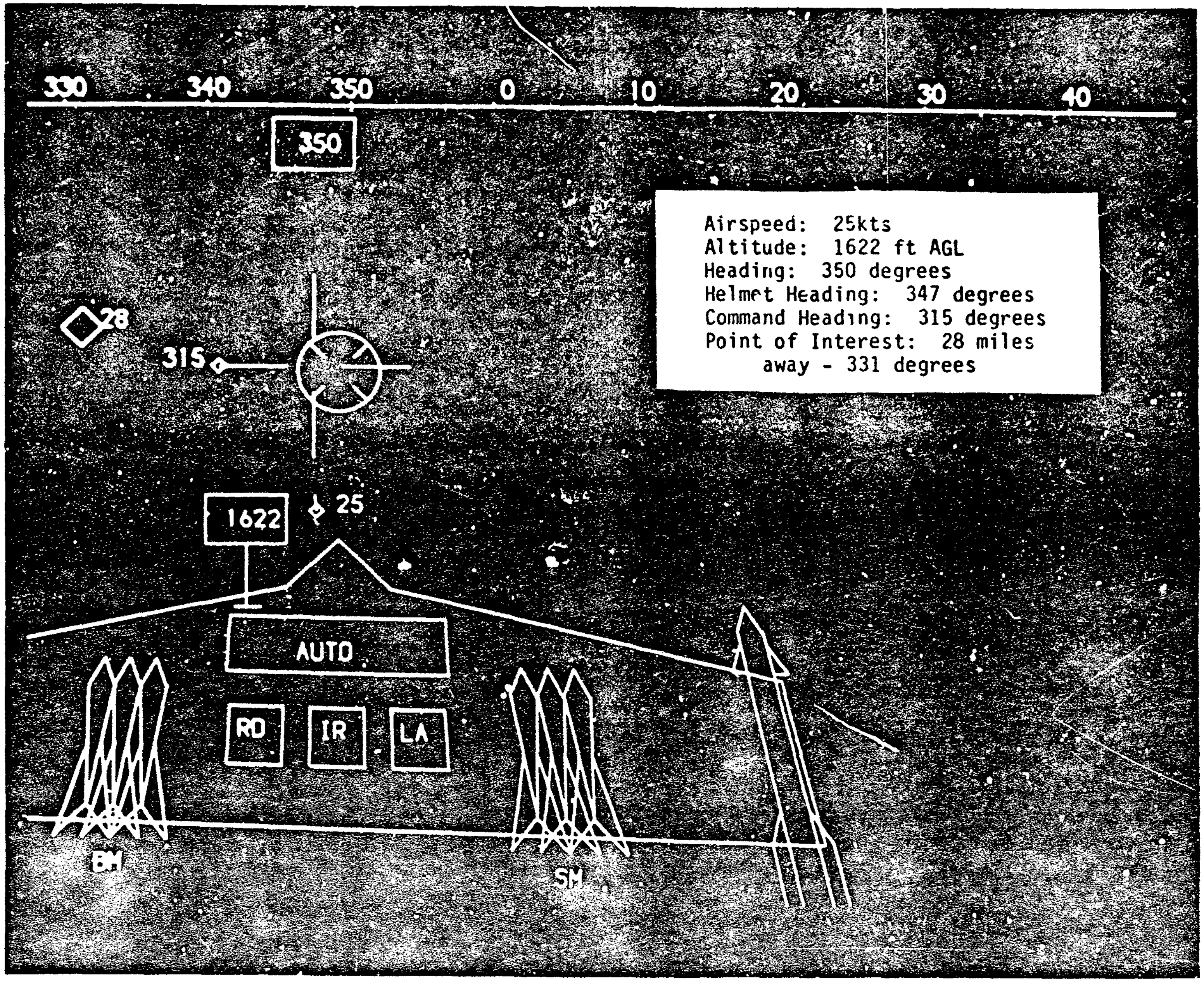
4.1 The simulation was developed to satisfy a number of requirements by the DOD Office and AFAMRL. Below is a listing of these requirements, together with an indication of how they were satisfied:

4.1.1 The gaming area was to correspond to a point in the mission scenario as generated under the Phase I effort. (This point was selected to be 10Km from the forward line of troops (FLOT).)

4.1.2 The pilot's task had to be realistic within the mission scenario. (The pilots were tasked to follow the flight director information, which would vector them to the primary target, a tank.)

4.1.3 Other ground and airborne threats were to be encountered on the way to the primary target. (A simulated Hind helicopter, an AAA site, and three SAM sites were located at random within a 10Km to 20Km radius from the fixed start position. Although the tank was passive, the other threats were capable of lethal weapon deliveries if the LHX was within their range and not masked by terrain. The Hind, once shot down, was always replaced by another Hind somewhere within the threat area after approximately five seconds.)

4.1.4 The state of the target acquisition systems associated with each of the threats had to be communicated to the pilot. (Recorded voice announcements were provided to the pilot whenever the LHX was radiated



Airspeed: 25kts
Altitude: 1622 ft AGL
Heading: 350 degrees
Helmet Heading: 347 degrees
Command Heading: 315 degrees
Point of Interest: 28 miles away - 331 degrees

Figure 1

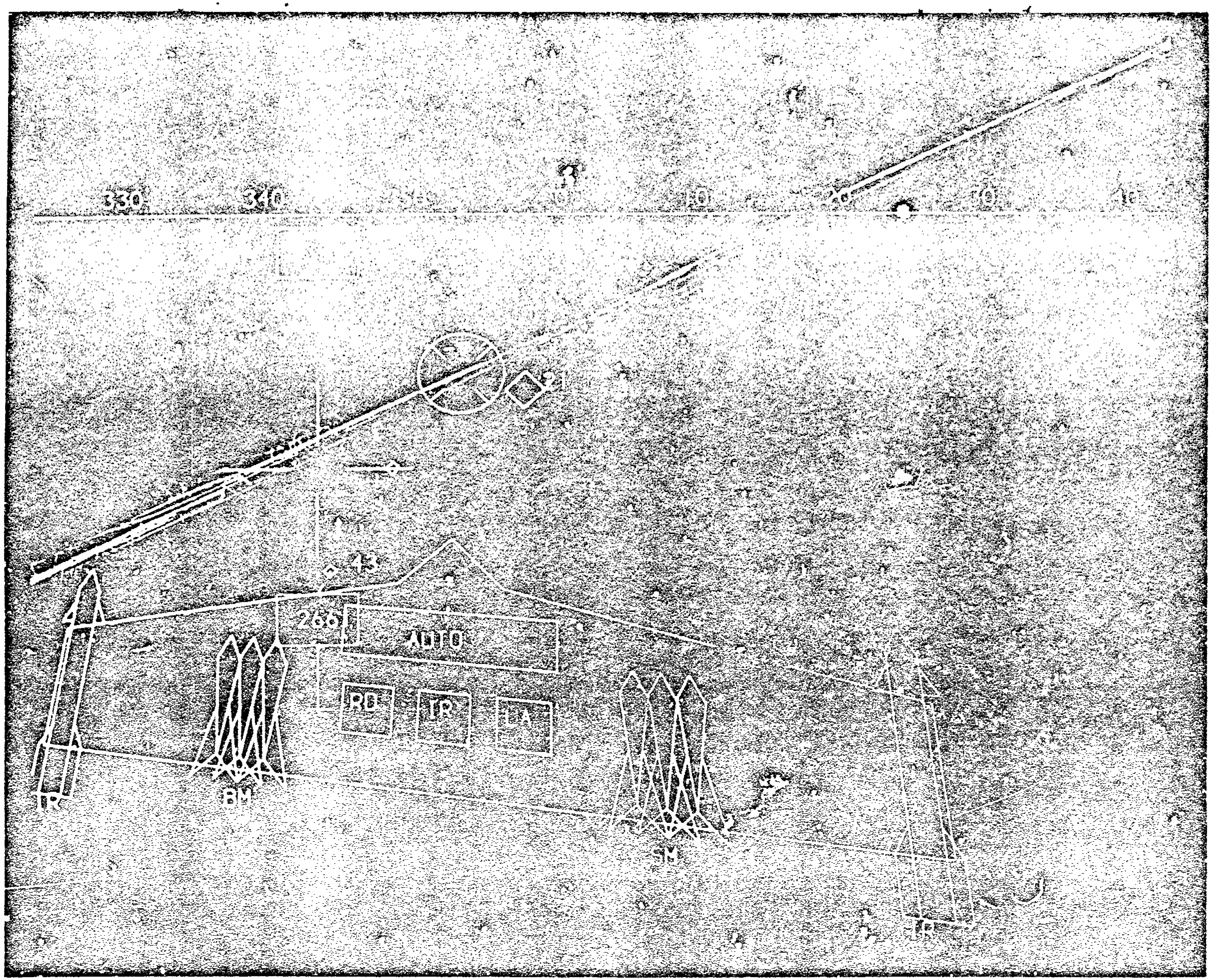


Figure 2

Virtual Cockpit with Terrain Portrayal. (Solid, dashed, and blanked lines indicate land, marsh by a threat's emitter, and not masked by terrain. Announcements provided target type (i.e., infrared or radar target), clock position and range information. Threat emitter mode changes (i.e., search, acquisition, tracking, or launch) were signalled to the pilot via a set of threat warning tones generated according to Army supplied information.)

4.1.5 A side task was to be provided to assure pilots were task loaded at all times. (An auditory Sternberg task (see Sternberg, 1975) was imposed in which pilots were requested to indicate, via a button on the collective, whether an alphabetic character presented over the headset was or was not one of a previously memorized set of items. A new item was presented each time the last item was responded to, or after three seconds if there was no response.)

4.1.6 Sufficient LHX armament was to be provided to enable the pilot to knock out the primary target (tank) as well as deal effectively with the Hind, the AAA and SAM sites. (Four beam rider, two infra-red (IR) and two "fire and forget" missiles, together with a 30mm cannon with tracers, were provided.)

4.1.7 ECM/ASE capabilities were to be provided under pilot control. (Pilots could select IR or radar countermeasures individually, or place both in an automatic mode for intervals of 30 seconds each, at which time they were not vulnerable to IR or radar detection by threats.)

4.1.8 Measures of workload resulting from various FOV's were to be generated. (Subjective evaluation of workload was provided through a broad range of both structured and unstructured questionnaire responses. In addition, Subjective Workload Assessment Technique (SWAT) ratings (see Reid et al, 1981; Reid, 1982; and Eggemeier et al, 1982) were obtained on the major mission task elements.

4.2 The pilots serving as subjects in this effort were all highly experienced. All four had from four to seventeen years Army service and from four to thirteen years as helicopter pilots. Two had about 1,000 hours combat helicopter time and the other two had none. In all, experience with nap-of-the-earth (NOE) flying ranged from 150 to 3,000 hours, with an average of over 960 hours, while their night flying time ranged from 40 to 600 hours, and averaged over 270 hours.

5.0 PROCEDURE.

Prior to the simulation sessions, the pilots were provided an indoctrination briefing and a set of written instructions (see Appendix) as to what they would see, hear and do during the four days of experimentation. They were also asked to perform the required SWAT card sorting task, from which interval scale values are generated for various combinations of effort, time, and stress levels of workload. Since the effectiveness of the threat announcement, warning tones, and auditory Sternberg task relied on normal hearing capabilities, each pilot took an audiological examination, the results of which showed totally normal functioning for all pilots.

Once the pilots were comfortable with the scenario that they would encounter and with their response capabilities, each was given approximately one hour practice in VCASS. The first half of this period was spent flying with the widest FOV that they would use (120 degree binocular). The remainder was spent practicing with the other FOV's used in the study (i.e., 90 degree binocular, 40 degree binocular, and 40 degree monocular). Although it was anticipated that the unfamiliar flight dynamics and low resolution terrain portrayal (grid lines each 1500 feet, and only in one direction) would present an extraordinarily difficult flight control problem, time constraints did not allow more practice. Based on the experience of the practice trials, task difficulty was reduced somewhat by modifying the threat emitter algorithms so that the LHX could avoid being radiated by maintaining his altitude at or below 500 feet AGL. At about this altitude, the grid lines simulating the terrain provided adequate visual cues for VFR maneuvering.

After practice, each pilot flew the simulator in a series of 24 five-minute sorties during the next three days. The sequence of the four FOV conditions, the random position of threats to be encountered (24 different data sets were used) , and the size of the Sternberg memory set to be responded to in any given session were counterbalanced so that every condition preceded every other condition an equal number of times. Each pilot flew a block of six sorties for each condition. Each sortie was typically separated by a three-to-four minute inter-trial interval (ITI), during which time the pilot rated the difficulty of performing the previous mission's tasks according to the extent of time load, mental effort, and psychological stress experienced. These SWAT ratings were collected on the tasks of: a) following a command heading to the enemy tank while flying contour and/or NOE; b) defending against and/or destroying ground threat systems; and c) contending with the Hind by attacking or defending. The ITI also provided time for the pilot to memorize the next memory set (either one or four alphabetic characters) for the next trial. This interval was also required to load the data set and initialize the VCASS computers for the next trial.

At the conclusion of the experimental sessions, each pilot completed a questionnaire related to: a) the effects of FOV size on his ability to perform various aspects of the mission; b) control/display features of the simulation itself; c) his ability to perform the mission, presuming a range of cockpit technologies; d) prioritized, essential cockpit information for mission performance; and e) the impact of an additional crewmember on mission performance.

6.0 RESULTS.

6.1 Questionnaire Responses.

6.1.1 Mission Effectiveness. Table 1 shows the average of pilot ratings (on a seven-point scale) of the effects of FOV size on overall mission success, as well as on the discrete functions of piloting, navigation, target acquisition, weapon delivery and survivability. Anchor points were provided at both ends of the scale. A rating of one indicated "prohibited effective, safe mission completion", while a rating of seven indicated "enabled effective, safe mission completion".

TABLE 1

MEAN OF PILOT RATINGS OF FOV EFFECTS ON MISSION AND MISSION FUNCTIONS

	Field-of-View (FOV)			
	40 mono	40 binoc	90 binoc	120 binoc
Overall Mission	1.75	2.75	5.0	5.5
Piloting	2.25	2.75	5.7	6.0
Navigation	2.25	3.5	5.5	6.0
Target Acq.	1.75	3.25	4.5	4.75
Weapon Del.	2.75	3.75	5.25	5.0
Survivability	1.5	2.5	5.25	5.75

The generally orderly effect of FOV on estimated capability to complete the mission is obvious. The small inversion between the 90-degree and 120-degree FOV's for the weapon delivery function, together with the relatively compressed range of ratings for that function, reflects the pilots' judgement that a large FOV is simply not a major factor for that function.

6.1.2 Situational Awareness. Responses for each of the FOV's on a similar seven-point scale ranging from "did not provide acceptable situational awareness" to "provided optimum situational awareness" produced average ratings of 1.0, 2.5, 5.0, and 5.25 for FOV's of 40-degree monocular, 40-degree, 90-degree, and 120-degree binocular, respectively. Pilots thus preponderantly favored the 90- and 120-degree FOV's and regarded them as virtually equivalent in their effects on this factor.

6.1.3 Pilot Acceptability. When asked to estimate the degree of acceptability for each of the FOV's by the pilot community, the subjects used a seven-point scale to rate the four options. A score of one indicated the FOV "would be rejected" and a score of seven indicated it "would be accepted/desired". The 40-degree options provided average ratings of 1.25 and 2.75 for the monocular and binocular cases, respectively, while the 90- and 120-degree FOV's generated ratings of 5.5 and 6.0. Again, the near equivalency of the 90- and 120-degree FOV's was maintained.

6.1.4 Minimum FOV Required. Responses were divided when subjects were asked to estimate the minimum FOV required to perform a helicopter mission. One subject felt the 40-degree binocular FOV was the minimum display requirement, two indicated a display in the 60- to 90-degree

FOV range as the minimum, and one felt a 90-degree FOV to be the minimum.

6.1.5 Effect of FOV on Single-Pilot Performance. Pilots were asked t narratively describe the effect FOV would likely have on single-pilot performance for air-to-air, anti-armor, and reconnaissance missions. Their statements indicated that, for the air-to-air mission, greater FOV's should increase the accuracy of and decrease the time required for target acquisition. It was felt that a narrow FOV would limit maneuverability and decrease acquisition capability. A concern was expressed that the high workload resulting with a narrow FOV would adversely affect survivability. All pilots wanted as wide a FOV as possible for the air-to-air task and one emphasized the importance of the vertical FOV saying at least 120 degrees was required.

There was less agreement among the pilots regarding FOV effects on the anti-armor mission. Although two pilots felt they needed as large a FOV as possible, the other two implied a smaller FOV would be acceptable. One stated that targets would be easily acquired and engaged with the 40-degree binocular FOV and that the 40-degree monocular FOV was acceptable in some cases. Three pilots felt the reconnaissance mission required as large a FOV as possible, while the fourth stated that a smaller FOV would be acceptable.

6.1.6 Hovering. Due to time limitations, only three of the four pilots were able to perform and evaluate the hover maneuver for each o the FOV's. This rating was again made on a seven-point scale ranging from "very difficult" to "very easy". Although the flight dynamics model employed made hovering difficult, pilots conjectured that the progression of FOV's studied would result in ratings averaging 1.33, 3.0, 5.0, and 6.0, respectively. The judged superiority of relatively larger FOV's is again evident.

6.1.7 Graphics Complexity/Density. Since the graphic portrayal of th virtual cockpit competes perceptually with the line graphic rendering of the terrain, an important question arises as to the optimum relativ complexity/density of these two display components. Subjects were therefore asked to rate the existing versus the "ideal" complexity/density of the virtual cockpit and terrain portrayal. The pilots indicated the existing complexity/density of the virtual cockpi information was approximately what they would envision in the "ideal" display, but that the existing complexity/density of the terrain portrayal graphics was far lower than desired. As expected, the lack of horizontal grid lines to provide closure, speed, and contextual cue was cited as a major drawback to VCASS terrain portrayal graphics.

6.1.8 Information Prioritization. Responses to a query to list and prioritize elements of information essential for mission performance generated a diverse range of responses with little agreement among pilots as to either the nature or priority of information required. This result probably rather realistically reflects individual preferences, tactics development, and past experience of the pilots sampled, and also correlates with the diversity (i.e., lack of standardization) of allocation of cockpit real estate to various functions across existing aircrew stations. In general, however, information elements high on the list included those most directly related to survival (e.g., threat location and status, airspeed, altitude and heading, power management, and visual cues for NOE flight). Elements still essential, but lower on the list, included system status/warnings, weather, location of friendlies, and armament configuration and ordnance inventory.

6.1.9 Number and Duration of Flights. Based upon their VCASS simulation experience, and assuming similar capabilities with an operational system, pilots were asked to estimate the number of missions per day they could fly alone as a single pilot, as opposed to having a companion crewmember present, as a function of mission length. Considering mission lengths of less than one hour, one to three hours, and from over three to five hours, the number of flights, averaged across estimates from four pilots, is shown in Table 2. The estimated increase in number of flights afforded by a second crewmember was consistent, but small.

TABLE 2

ESTIMATED AVERAGE NUMBER OF FLIGHTS ONE VERSUS TWO CREWMEMBERS COULD FLY PER DAY

		Crew Size	
		One Crewmember	Two Crewmembers
Mission Duration	Less than 1 hour	3.6	3.75
	1 to 3 hours	2.0	2.75
	3 to 5 hours	1.0	1.5

6.1.10 Effects of Cockpit Technology on Pilot Performance. Pilots were asked to assume that three separate display technologies could each be applied in either one- or two-pilot configurations for an advanced rotary wing, multi-role, multi-mission vehicle. The technologies to be considered were: a) conventional Cobra helicopter type displays; b) multifunction panel CRT's; and c) a virtual panoramic wide FOV display. The pilots were then asked to estimate the percent of total mission tasks that could be performed by a single pilot, as well as by a two-crewmember team, with each of these display technologies. The average responses from the four pilots are shown in Table 3. While they obviously felt a greater proportion of mission tasks could be completed by two crewmembers, as opposed to one, the pilots thought the greatest increment in judged successful task performance across display technonogies was associated with the jump from multifunction panel CRT's to the VPD technology.

TABLE 3

ESTIMATED PERCENT OF TOTAL TASKS ABLE TO BE PERFORMED BY ONE VERSUS TWO CREWMEMBERS AS A FUNCTION OF PRESUMED DISPLAY TECHNOLOGY

		Crew Size	
		One Crewmember	Two Crewmembers
Display Technology	Cobra	35%	60%
	Multifunction Panel CRT's	54%	78%
	Virtual Panoramic Wide FOV Display	89%	95%

6.1.11 VCASS Simulation Features. When asked to express their likes and dislikes about the VCASS simulation, the pilots reported positive remarks concerning the opportunity to gain hands-on experience exploring the various FOV's and simulated avionic advancements, including long-range target acquisition and engagements, voice warning concepts, and virtual display graphics (i.e., use of aircraft wings for arms status, ECM/ASE status, and attitude cues). The pilots also felt their VCASS experience provided insight into their own ability to selectively accept/reject information during varying workload levels. They cited negative comments related to the lack of NOE terrain references, the lack of high fidelity helicopter dynamics, the mission's ambitious startup (i.e., rapid onset of events in each sortie), their inability to maintain consistent airspeed and altitude, difficulty separating the helmet display from the terrain line graphics, the excessive number of audio tones they had to memorize, and difficulty identifying points of light (far off targets) on the HMD. In general, however, the results of this query reflected a high level of satisfaction with the virtual display concepts, and served to identify weaknesses in the simulation which will become candidate enhancements for future simulations.

6.1.12 Switching Options. Pilots were requested to assess the switchology available to them during the VCASS simulation and to identify problems and needs. They expressed a desire for a fire control reticle when viewing at the 10:1 magnification and for a radio transmit switch. Confusion was experienced, since the VCASS missile launch button serves as the force trim interrupt on current Army helicopters. Suggestions were made to spread the switches out to accommodate use by different fingers, to move the rocket fire button to the AH-1 Cobra location, and to relocate the altitude hold switches to a more accessible location.

When asked if additional switches or switch modes would help or hinder the pilot, their responses were conservative, cautioning against overloading the pilot by increasing switches or switch modes.

6.1.13 Additional Comments. When given the opportunity to provide additional comments, the pilots stated that they thought their ability would/did improve with each flight, and that perhaps the data could have been more reliable with increased practice time. They unilaterally expressed high regard for the current status of VCASS and for the virtual cockpit concepts explored.

6.2 Objective Data. Not unexpectedly, none of the more objective measures of performance (including the SWAT, Sternberg, and a comprehensive set of offensive and defensive performance measures) showed any effects of FOV whatsoever. The reason, most likely, was due to the difficulty of the flying task, regardless of the FOV being used. The only statistically significant effect was associated with the orderly progression of learning by all pilots across all FOV's. That is, an analysis of variance of the number of threats killed by the LHX revealed a statistically reliable improvement across blocks of trials [$F(3..2)=6.19$; $p<.05$].

Wide differences were observed as to how each pilot approached the various mission tasks (especially offensive vs. defensive operations, and whether or not the Sternberg task was faithfully performed). For example, at any given point in the series of sessions, one pilot might have concentrated on learning how to maneuver to gain an advantage on the Hind, while another pilot might have expressly avoided the Hind and pursued the AAA or SAM sites, while a third pilot might have avoided and countered all threats to the maximum extent, while concentrating on the primary objective of flying as direct a course as possible to the tank. The purposefully unstructured nature of the development of these individual approaches (tactics) to the solution of the problem generated another source of variability in performance that could not be stabilized within the brief exposure period available.

7.0 SUMMARY AND CONCLUSIONS

In summary, our general observations are as follows: a) a low rate of learning (shallow learning curve) was experienced by the pilots, most likely due to a combination of unfamiliar helicopter dynamics and sparce visual perspective cues for position and motion feedback with respect to terrain features; b) the virtual cockpit provided wide latitude for individual formulation and employment of tactics, which translates directly to both more capability for the pilot, as well as more erratic behavior of any single measure of workload or mission success; and c) future simulations will benefit greatly from the information gained in this exercise.

Although simulation enhancements under Phase II of this joint Army/AFAMRL effort must await further tradeoff analyses of alternative hardware and software investments, our lessons learned are clear and are as follows: a) the flight dynamics model must be improved to the point that learning to fly the dynamics of the simulator takes little or no time; b) to be useful, the panoramic visual scene must be upgraded to better accommodate the relatively low and slow flight regime of the helicopter; c) techniques need to be explored to reduce the present competition between the virtual cockpit and the line graphic terrain; and d) future studies must allow for thorough trainin of pilots in the simulator, prior to the start of any data collection and evaluation procedure.

Finally, and somewhat surprisingly, in recognition of the admittedly crude and brief nature of this simulation exercise, pilot acceptance of the first generation virtual cockpit concepts was positive and unanimous. The dedication and attitude of the pilots toward this exploratory effort was remarkable and thoroughly appreciated.

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Appendix

Indoctrination Instructions for VCASS LHX Pilots

Welcome to AFAMRL and the first generation of LHX mission simulations using the VCASS (Visually Coupled Airborne Systems Simulator).

The primary purpose of our present study is to familiarize you with the VCASS facility and provide a structured set of mission, visual field-of-view (FOV) and secondary tasking conditions while you fly directed courses over a rudimentary terrain representation.

You will have approximately one hour of practice time (more if you desire) in VCASS to become familiar with the helmet-display system, aircraft controls, control dynamics, terrain portrayal, ASE, and threat activities represented. During approximately the first half of this period, you will have a 120° binocular FOV on the Helmet Mounted Display (HMD). Since we measure head position, the scene you see depends on where you turn your head, i.e., where your helmet aims. Prior to the run the helmet will be adjusted to attain as comfortable a fit as possible while maintaining the full FOV available throughout all desired head positions. You may also adjust the HMD optics to accommodate your individual eye separation distance, as well as boresight the display. The location and operation of cockpit controls will be fully explained.

During the simulation you will hear audio tones representing various modes of enemy threat systems. You will have ASE/ECM capabilities as described to you shortly. Procedures for aiming and firing weapons will also be explained.

After you feel comfortable handling the flight control aspects of the simulator, you will be asked to follow the command heading to the target, a tank, in order to destroy it as soon as possible. Since, during this early period, you have not been asked to attack or defend against the HIND or against ground-based threats, you may be (repeatedly) shot down by enemy guns or missiles. When this happens, your display will be automatically blanked for 1 to 2 seconds. When your display reappears you will be at your prior coordinate position, but at 100 feet AGL. After destroying the tank, you may go after the HIND or any of the AAA or SAM sites. Throughout this and the remainder of the practice sessions, as well as the experimental sessions, you will be confronted with a total of five threat systems: one AAA site, three SAM sites, and the HIND helicopter (the tank remains passive at all times). The three SAM sites represent relatively short, medium, and long acquisition and missile range capabilities, respectively. Further details on these threats will be provided later. Keep in mind that the HIND will chase you until you shoot it down. At that time, you will see a burst signalling a hit (and kill) and approximately five seconds later a new HIND will appear at a random location somewhere within the gaming area. In contrast, the tank, AAA, and SAM sites will, on any particular trial, stay dead once they are destroyed. The remainder of your practice trials are to familiarize you with the smaller fields of view (FOVs) as well as the other tasks that you will perform within and between the experimental sessions. The other FOVs will be a 90° binocular, a 40° binocular, and 40° monocular. You will be told which you are viewing at the start of a series of trials using a particular FOV.

We want a more or less continuous measure of your workload and how much reserve capacity you have remaining at any point in the mission. To obtain the data, you will perform a short-term memory task during the mission. This task is known as a Sternberg task, and will require you to respond "yes" or "no" to each of a series of alphabetic characters that either are or are not one of a previously memorized character set. The procedure for the Sternberg is as follows. Prior to the start of a trial, you will hear either one or four alphabetic computer-synthesized speech characters over the headset. As a backup to this auditory presentation, you will be given a printed card with one or four characters, as appropriate, to memorize. When you are sure that you have them memorized, and give the card back to the experimenter, the trial will start. When items are presented over the headset, indicate whether each item (or probe, as it is called) is or is not one of the items that was on the card by pushing the rocker switch on the top, inboard side of the collective. Please rest your thumb on this switch at all times while flying so that we get accurate response times. Push the switch forward if the probe item is one in the memory set, and backward if it is not. Remember, forward for "yes", back for "no". Keep in mind that your main task is still to fly the aircraft, go after the tank, and deal with the various threats as best you can in order to stay alive. You are allowed to not respond to the Sternberg items during those periods in which you feel that you have no capacity to perform anything but the flight task. However, in the interests of data validity, please try to keep up with the Sternberg task. If you have made no response to a probe item after three seconds, a non-response will be recorded and a new probe item will be presented. The visual scene available permits you to terrain mask yourself from enemy acquisition and missile homing devices. It will also be possible, under certain conditions, for you to outmaneuver launched enemy weaponry. In general, the greater your speed and the closer your cross-path trajectories are to 90° (yours vs. the missile or gun rounds) the higher your chance of being able to avoid the hit by making a jinking maneuver.

In the event of an enemy hit on your aircraft, or if you crash at any time, the same 1 to 2 second screen blanking will occur followed by a reset to 100 feet AGL.

Except for your original approximately 30 minute practice session, every other trial will last for five minutes. At the conclusion of each trial you will be asked to perform SWAT (Subjective Workload Assessment Test) ratings for the previous trial. Once the practice trials have been completed (one or two five minute sessions at each of the other FOVs), the experimental trials will start. There will be about a three minute break between trials, during which you will make the SWAT ratings and commit the Sternberg item(s) to memory, in preparation for the next trial.

Each trial will start with you hovering over the same point on the simulated terrain. The HIND, AAA, and SAM threats will be positioned randomly from 10 to 20 km away. In each new trial threats will be in different locations, always no nearer than 10 km and no further than 20 km away. Use available terrain features to mask yourself, use your gun, missiles, and ASE/ECM to counter threats when appropriate and jink to avoid oncoming missiles or cannon fire.

GOOD LUCK!!!

Are there any questions?

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ANNEX R-VI

HUMAN FACTORS ASSESSMENT OF VOICE TECHNOLOGY FOR THE LIGHT HELICOPTER FAMILY (LHX)

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Annex VI to Appendix R

HUMAN FACTORS ASSESSMENT OF VOICE TECHNOLOGY FOR THE LIGHT HELICOPTER FAMILY (LHX)

R-VI-1. The technical memorandum, "Human Factors Assessment of Voice Technology for the Light Helicopter Family (LHX)" is reproduced on the following pages.

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Technical Memorandum

HUMAN FACTORS ASSESSMENT OF VOICE TECHNOLOGY FOR THE LIGHT HELICOPTER FAMILY (LHX)

Frank J. Malkin
Kathleen A. Christ

February 1985

ABSTRACT

This report was written in support of the technology trade-off analysis (TOA) performed for the Light Helicopter Family (LHX). The human factors aspects of applying voice technology to an LHX aircraft with full-scale development in 1987 are addressed. A description of voice technology and its advantages and disadvantages is provided, potential applications for voice technology in an LHX aircraft are discussed, the issues related to voice technology applications are reviewed, and conclusions are drawn.

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HUMAN FACTORS ASSESSMENT OF VOICE TECHNOLOGY FOR THE LIGHT HELICOPTER FAMILY (LHX)

INTRODUCTION

An Army helicopter pilot's workload is unique. The visual workload is saturated due to the "out-the-window" visual demands of flying at or below treetop level, sometimes at night and in adverse weather conditions. The manual workload is equally saturated because current helicopters require both hands and both feet for control. The Army normally employs a copilot in its aircraft. The workload of the copilot in a tactical mission is as great if not greater than that of the pilot. One of the responsibilities of the copilot is navigation. Comparing terrain features on a map with the actual terrain features on the earth's surface is an especially demanding task when accomplished while flying at altitudes below 100 feet. While the identification of terrain features primarily requires the visual attention of the copilot, his hands are also busy handling maps, checklists, and tactical notes. Thus, the pilot and copilot in current Army helicopters experience high levels of workload while flying and navigating. This does not include the additional workload resulting from other tasks such as communications, subsystem monitoring, threat detection and avoidance, and mission accomplishment (weapons firing, reconnaissance, etc.)

The US Army is formulating concepts for the development of a family of light helicopters (LHX). Concepts for the cockpit include a high level of automation which may enable the demanding tasks described above, which are currently performed by two crewmembers, to be performed by a single pilot. This automation would incorporate high-technology sensors and advanced displays and controls using artificial intelligence and voice technology.

Voice technology is being considered for the LHX because it provides an alternative means of interacting with onboard systems. It is anticipated that the visual and manual workload of aircrews can be reduced somewhat by converting some of the visual and manual tasks to speech and auditory tasks.

PURPOSE

This paper addresses the human factors aspects of applying voice technology to an LHX aircraft with full-scale development in 1987. A description of voice technology and its advantages and disadvantages is provided, potential applications for voice technology in an LHX aircraft are discussed, the issues related to voice technology applications are reviewed, and conclusions are drawn.

VOICE TECHNOLOGY

Voice technology, which encompasses computer generation and recognition of speech, provides a potential for reducing the visual and manual workload by changing some of the pilots' visual and manual tasks to auditory and speech tasks. Computer generation of speech (speech generation) is the means by which the pilot can receive systems information aurally through his headset. Computer recognition of speech (speech recognition) provides the pilot with the capability of interfacing with aircraft systems by speaking to them.

Speech Generation

Speech generation refers to verbal messages generated by an onboard computer system which provide cautions, warnings, or other information to the pilot.

Currently, there are two processes for generating speech which we will call digitized speech and synthesized speech. Digitized speech is produced by recording the human voice and converting the voiced message to a digital form and storing it in computer memory. When the message is to be transmitted to the pilot, it is converted back to its original spoken form. Synthesized speech is produced totally by machine. The human vocal tract is modeled electronically, and the phonemes (approximately 40 basic sounds that make up the English language) are electronically reproduced to create speech-like quality. There are advantages and disadvantages to each process, which will be discussed later.

Speech Recognition

Speech recognition permits the pilot to interact with aircraft subsystems using speech. To accomplish this, the speech recognizer analyzes and converts the aviator's spoken commands to digital signals that control aircraft systems. The primary advantage of speech recognition technology is that it permits the pilot to interact with controls and displays using spoken commands while leaving his hands and eyes free for critical flight and navigation tasks.

State-of-the-art speech recognition technology is currently limited primarily to speaker-dependent, isolated word recognition systems. "Speaker dependent" refers to the fact that, prior to use, the system must be provided with a sample of how each operator pronounces the words in a predetermined vocabulary. This is commonly referred to as training the system. Depending upon the manufacturer's design, anywhere from 1 to 10 samples of the potential user's speech pattern must be provided for each vocabulary word. These samples are then stored in memory as references for later comparisons. When in use, the system recognizes words by comparing current utterances with the samples stored in memory and selecting the closest match.

"Isolated word recognition" refers to the characteristic of current systems where utterances are typically less than 2 seconds in duration and a distinct pause is required between each vocabulary item.

These speaker-dependent, isolated word speech recognition systems can be used with vocabularies consisting of 200-300 words. Used in a quiet setting by a limited number of selected personnel, these systems are capable of obtaining recognition accuracy rates of 99 percent or more. This vocabulary size appears to be sufficient for employing voice technology in aircraft. Recognition accuracy will be discussed later.

The limitations of these speaker-dependent, isolated word systems are the need to train the system prior to use and the need to pause between each utterance. Training the system can be time-consuming, and pausing between utterances slows data entry and creates an unnatural form of speaking.

Manufacturers of speech recognition devices are attempting to develop systems that will overcome these limitations. Speaker-independent systems allow anyone to use the speech recognizer without first having to provide speech samples. This is difficult to achieve because of the variability in speech patterns among individuals.

Connected word speech recognition systems allow utterances of several seconds in duration regardless of the presence or absence of pauses. The vocabulary for connected word recognition is typically structured and limited in size. A typical application for connected word recognition is the entry of digits such as the coordinates for navigation waypoints.

Continuous speech recognition allows a totally natural form of speech with an unrestricted vocabulary--the way we speak with each other. The difficulty with obtaining continuous speech recognition is that word boundary detection is an important aspect of speech recognition technology. With completely natural speech, current machines cannot reliably determine when one word ends and the next begins.

Most of the speech recognition devices available on the market today are the speaker-dependent, isolated word type. Several manufacturers now offer speaker-dependent, connected word systems; and some manufacturers are promising speaker-independent systems in the near future. Reliable and cost-effective continuous speech recognition remains a long-range goal. Speech recognizers for early LHX aircraft will probably be speaker-dependent, connected word.

A limited number of vendors in the United States who are developing prototype speech recognizers specifically designed to withstand the noise, vibration, and temperatures associated with aircraft. Two of these systems, manufactured by Texas Instruments and Lear-Siegler, are currently being tested by the US Air Force under the Advanced Fighter Technology Integration (AFTI) program. Some of the results of these tests will be discussed later. The Navy is initiating voice technology flight testing in an F-18 fighter aircraft. The Army has plans for flight testing of voice interactive systems in a UH-60 utility helicopter during the summer of 1985.

One of the prototype voice systems undergoing flight testing incorporates both speech recognition and speech generation in one unit. The hardware consists of a processor and a control panel. The following characteristics of this system are furnished to provide a general concept of the power, size, and weight requirements of airborne voice interactive systems.

POWER: 28V DC; 115V AC, single phase, 400 Hz

DIMENSION:

Processor - 17 x 9 x 7-1/4 inches
Control Panel - 6 x 5-1/4 x 2-1/4 inches

WEIGHT:

Processor - 42 pounds
Control Panel - 2.3 pounds

It is anticipated that the weight of future production voice systems could be reduced to 10 pounds or less with a corresponding reduction in size.

Advantages and Disadvantages of Voice Technology

The primary advantage of using voice technology in the cockpit is that the crewmember(s) can interact with aircraft subsystems while leaving the eyes and hands free for critical flight and navigation tasks. Other advantages of voice technology are that it:

a. Can be faster than other modes of communication.

b. Can be more accurate than other modes of communication.

c. Is the most natural form of communication.

d. Requires less effort and motor activity than other communication modes.

e. Can be operated in darkened environments.

There are also disadvantages to using voice technology in the cockpit. The high noise levels generated by the helicopter may affect the performance of voice technology systems. Also, changes in the operator's speech due to fatigue, stress, colds, or physical activity may affect speech recognizer performance.

These advantages and disadvantages will be expanded upon when voice technology issues are addressed later in this paper.

POTENTIAL VOICE APPLICATIONS

As mentioned previously, speech recognition provides an alternative to manual activation of switches and controls; and speech generation provides an alternative to the visual display of messages and information.

To determine which tasks are best accomplished by speech recognition and speech generation, a detailed task and functional analysis should be performed viewing the cockpit as a total system, including the mission and the battlefield environment.

Present attempts to assess potential applications of voice technology for the LHX are hampered by the inability to perform the desired detailed analysis. The configuration of the LHX cockpit and the advanced technologies to be used in the cockpit are not yet fully defined.

However, it is possible to generally project potential applications for voice technology in a future, single-pilot LHX aircraft by examining the functions involved in flying the aircraft and performing the mission.

Unmask/Remask

It is not anticipated that a task as critical as controlling a helicopter during nap-of-the-earth flight will be accomplished to any large degree by voice. However, it is possible that voice could be used for limited flight control such as "bob-up" and "remasking" maneuvers.

Consider a task in which a single pilot is required to "bob up" from a hover while simultaneously operating a target acquisition and detection system. It would appear to be impossible to perform both tasks simultaneously. With the computer technology expected to be available for the LHX, it would be a simple matter for the pilot to command "bob up" and the aircraft to respond by automatically climbing vertically to a preselected hover altitude. When ready to descend, the pilot commands "remask" for the aircraft to return automatically to its original hover point.

Target Acquisition and Detection Systems

Speech recognition could be used by the crewmember to interact with the target acquisition and detection system. Weapons, sensors, fields-of-view, and armament could be selected by verbal command.

Communications

It is envisioned that by using speech to tune radios, it may no longer be necessary for the pilot to memorize or make reference to printed lists of numeric radio frequencies. The radio could be set to the correct frequency or channel by saying the call sign of the station to be contacted. Feedback that the proper frequency had been set by the computer could appear on a display along with pertinent communications equipment operational instructions (CEOI) data.

Navigation

The results of several research studies indicate that entering complex data by speech while flying at nap-of-the-earth may be less disruptive to the flight control of the aircraft than entering data by keyboard. If a visual map display is available, the entry of navigation waypoints can be greatly simplified by combining the use of speech recognition technology and a touch-sensitive panel installed on the map display. The pilot could point to a geographical location on the map and say, "waypoint one." The waypoint would be entered into the system without having to read a string of alphanumeric characters. Speech recognition could also be used to change scene content or the scale of the map.

As with current visual displays, it will probably be necessary to ensure that the displays in the LHX do not become cluttered by attempting to present too much information. Information such as distance to waypoint could be eliminated from the display using voice interactive technology. When this information is needed, the pilot would request the information using speech recognition and would receive the information through his headset via speech generation.

Subsystems Status Monitoring

It is likely that in an LHX aircraft, the computer will be used to monitor the subsystems (i.e., engine, transmission, and hydraulics), freeing the pilot from this task. When the computer senses that a subsystem's upper or lower limit is being reached, it will alert the pilot. This can be accomplished visually, auditorily, or by a combination of both. Cautions and warnings can be easily presented by speech generation. It appears that only high-priority warning messages will be presented by voice. For lower priority cautions and warnings, voice could be employed to call attention to the visual display where the actual message is displayed.

Speech recognition could be used to request subsystem status when required by the pilot. Depending upon the nature of the information requested, it can be presented either visually on a display or aurally by speech generation.

Aircraft Survivability Equipment

Threat warnings should be among the highest priorities for speech generation messages. The AN/APR-39 Radar Warning Receiver is currently undergoing modification to include a speech generation capability. Speech-generated threat warnings will eliminate the current requirement of discerning and interpreting among a variety of tones to obtain threat information.

The preceding paragraphs are just a few examples of the possible applications for speech technology in an LHX aircraft.

Certainly, others have thought of additional applications. Again, the actual application for speech technology will depend on the specific configuration of the cockpit as well as the mission requirements.

VOICE TECHNOLOGY ISSUES

It appears that there are several potential applications for voice technology in the LHX cockpit. However, voice technology is not yet fully matured; and some important issues remain to be resolved before voice interaction can be successfully used in these applications. Computer recognition of speech is more difficult to achieve than is computer generation of speech. The issues affecting speech recognition are much more critical than those affecting speech generation and will require a greater effort to overcome. This section discusses the important issues as they relate to the LHX. The first six of the following issues relate to speech recognition; the last two relate to speech generation.

Recognition Accuracy

In the following discussions of speech recognition issues, repeated references will be made to recognition performance in terms of either accuracy or error rates. What has not been determined is what constitutes acceptable performance. Is 99-percent recognition accuracy required? Is 95 percent acceptable? The answer probably depends on the task being performed. The more critical the task, the greater the accuracy required. If voice is used to control weapons, greater accuracy may be required than if voice is used to scroll a "before takeoff" checklist. There is a wide range of recognition performance reported in the literature, but the level of performance that is considered to be acceptable has not been determined.

Manual versus Voice Data Entry

Computer technology will play a significant role in the LHX cockpit. The current method for entering data into a computer is through a keyboard or function keys of some type. Pilots flying at or below treetop level may not have "eyes and hands free" for keyboard operations. Several studies (1, 7, 11, 19) have been performed to determine if voice provides any benefits over the manual keyboard method of data entry. The results of these studies generally indicate that for simple digit entry tasks, keyboard is faster than voice but for more complex data entry tasks, voice is faster. Also, when data entry is performed concurrently with a task similar to flying, voice data entry is less disruptive to the task.

In one laboratory experiment (19), voice data entry, manual data entry, and a tracking task (keeping a randomly moving symbol centered along a horizontal line) were each performed as isolated tasks. Voice data entry and manual data entry were also performed concurrently with the tracking task. The data entry was varied so that sets of either 4, 8, or 16 digits had to be entered. The results were that, when performed in isolation, the mean time for manual entry was faster than voice by .05 seconds. However, when data entry was performed concurrently with the tracking task, the mean time for voice was faster by .40 seconds. For the set of 4 digits, the mean time for manual entry was faster than voice by .14 seconds. For the sets of 8 and 16 digits, the mean time for voice entry was faster by .18 and .48 seconds, respectively. All of these differences in times were statistically significant.

Manual entry had a higher error rate than did voice entry, both when performed as an isolated task and when performed concurrently with the tracking task. When performed in isolation, the mean error rate for manual data entry was

1.37 percent versus .504 percent for voice data entry. When performed concurrently with the tracking task, the mean error rate was 3.73 percent for manual data entry and .746 percent for voice data entry. This error rate represents human input errors. The mean error rate of the speech recognizer, as measured by the number of times the recognition unit misrecognized voiced inputs, was 17.94 percent. For purposes of this experiment, subjects were instructed not to correct errors. It is likely that if subjects attempted to correct machine misrecognitions, a significant degradation in speed of entry for the voice method would have occurred.

The results of this experiment were reported in 1979. Speech recognition algorithms have improved considerably since that time, and one would not expect an error rate this large with speech recognizers developed more recently. The experiment illustrates the potential advantage for voice data entry if speech recognition accuracy could approach 99 percent.

Another experiment, conducted by the US Air Force, compared manual and voice data entry in a more realistic aviation setting (1). Air Force pilots participated in this experiment using a fighter cockpit simulator. The pilots were required to enter data manually and verbally. Voice data entry and manual data entry were performed in isolation and concurrently with a simulated terrain flight task. In this experiment, manual data entry was faster than voice with mean times of 5.21 seconds for the manual method and 6.29 seconds for the voice method. However, there was a 400-millisecond response lag for each entry by voice due to the hardware configuration of the speech recognizer. If the 400 milliseconds were subtracted from each voice entry, the mean time would decrease to 4.60 seconds, which is faster than the 5.21 seconds for manual data entry.

Comparing the manual and voice methods of data entry when performed in isolation and when performed concurrently with the flying task, performance for the voice method remained similar in both conditions (6.21 versus 6.38 seconds); whereas, the performance for the manual method declined from 4.67 seconds when performed as an isolated task to 5.76 seconds when performed concurrently with the flying task.

Because of the pilot test participants' confusion regarding the proper procedure for correcting errors, general conclusions concerning a comparison of error rates between the manual and voice data entry methods could not be stated with any certainty. However, it was reported that voice data entry probably had a higher error rate as a result of misrecognitions by the speech recognizer. In this experiment, the speech recognizer had a recognition accuracy of 95 percent.

Flight performance was impacted least when data was entered by voice in that performance remained similar whether the flight task was performed in isolation or concurrently with data entry by voice. However, performance on the flight task deteriorated when accomplished concurrently with the manual method of data entry.

If speech recognition is used in the LHX, it is not likely that it will eliminate the need for some method of manual input in the cockpit. The research conducted to date indicates that when short digit strings are to be entered or when workload is low, manual entry of data may be more effective. However, for longer digit strings or complex data and when workload is high, voice entry of data may be more effective. It is important to point out that this research was accomplished using isolated word recognizers. The results may be different if connected word recognizers are compared with keyboard entry. At any rate, manual input of some type will probably be required as a backup to speech recognition systems.

Noise

Standard speech recognition devices have been shown to be extremely sensitive to background noises associated with the aircraft environment. If a speech recognition device is trained in a quiet environment followed by attempts to use it in a noisy environment, severe degradation in performance usually results (6, 7, 12, 17).

In research at the Avionics Research and Development Activity (AVRADA), Fort Monmouth, NJ, a speech recognition device that was trained in a quiet setting was then tested in a 107-dBA UH-60 noise environment (17). The noise environment was provided by playing taped UH-60 cockpit noise in a laboratory acoustic chamber. The accuracy rate with which the device correctly recognized vocabulary inputs was reported at 33 percent, which is well below the 99-percent accuracy rate obtained by the manufacturer in a quiet laboratory setting. One way of improving recognition performance in a noisy environment is to train the device in the noise environment in which it is to be used. When the device was trained and tested in the 107-dBA noise environment, the recognition accuracy rate increased to 78 percent. Another method for improving recognizer performance in noisy conditions is to separate or strip away the noise from the speech signal before the speech signal enters the speech recognizer. Using such a noise-cancelling device, AVRADA researchers attained accuracy rates of 80 percent and 83 percent with two test subjects when a speech recognizer (different manufacturer than that used in the previous test) was trained in quiet and then tested in 107-dBA, UH-60 noise.

Encouraging results using a speech recognizer in noise were obtained during a test conducted at the NASA-Ames Research Center, Moffett Field, CA, (6). The speech recognizer was tested in an acoustics chamber with eight users, all of whom had some previous experience with speech recognition systems. Previously recorded UH-1H cockpit noise was played through loudspeakers at 100 dBA. The recognizer was trained in quiet and tested in noise and also trained in noise and tested in quiet. From a total of 3,200 inputs by the eight test participants, only one error occurred.

Initial AFTI/F16 flight testing conducted with commercial speech recognizers resulted in recognition accuracy rates of 82 percent at 85 dB and 13 percent at 115 dB (23). The introduction of prototype militarized speech recognition devices designed for use in the hostile aircraft environment along with subsequent improvements to these systems produced accuracy rates of 85 to 90 percent at noise levels up to 110 dBA (21).

These research efforts indicate that a known steady-state noise can be accommodated to some extent by training techniques and by the use of noise cancellation features. Although the effects of intermittent noise such as rotor blade slapping or weapons firing have not yet been addressed, the progress made to date with steady-state noise is encouraging.

It would be beneficial in many areas if the LHX interior noise were specified to be at or below 85 dBA. It would enhance speech recognition performance and at the same time reduce pilot hearing loss and fatigue.

Stress and Mental Loading

Factors such as emotional and physical stress affect a person's voice, thus affecting speech recognition performance (2). When under stress, an individual's voice may change in pitch. Also, syllables may be slurred together, or speech sounds may be omitted altogether. If a speech recognizer, trained by an individual who is not under stress, is later used by the same individual in a stressful environment, speech recognition performance will be adversely affected. Most of the research in this area has been conducted at the Naval Post Graduate Post Graduate School, Monterey, CA, (2, 3, 4, 10, 16).

One of these research efforts investigated stress brought on by increasing the mental load of the operator (3). Test subjects trained and used a speech recognizer while not experiencing mental workload. The same test subjects used the speech recognizer while having to depress response buttons that corresponded to symbols that were randomly displayed. There were 23 percent more speech recognition errors when the test subjects were experiencing mental loading created by this "response button" task.

The Flight Dynamics Laboratory at Wright-Patterson Air Force Base, OH, attempted to elicit emotional voice stress responses from test subjects in a setting that would approximate that of a fighter aircraft cockpit (22). Using video displays in a wooden mock-up of an F-15 cockpit, test subjects (nonpilots) simulated controlling the aircraft and attacking targets of opportunity by operating a Colecovision system with the Cosmic Avenger game cartridge installed. The results of this experiment were that even with the small three-word vocabulary that was used, the speech recognition accuracy was as low as 50 percent for several test subjects. The researchers emphasize that this was a preliminary experiment; and, therefore, the results are not conclusive. However, these results support the findings of other laboratory research and indicate the need for additional research in flight-oriented situations.

In a more recent Naval Post Graduate School research effort, it was found that recognition errors due to stress could be reduced or eliminated when the operator trains the speech recognizer under corresponding stress (16). Based on these results, the researchers suggest that, as with environmental factors such as noise, recognition errors due to psychological factors such as stress and fatigue may be reduced by training and using the speech recognizer under the same stress conditions. The researchers are also quick to point out that attempts to provide samples of speech under various levels of stress, frustration, and fatigue are often impractical.

Research into the effects of stress exposes the sensitivity of current speech recognition systems to changes in the operator's voice and speech. Because it is difficult to produce highly stressful situations in research, the work referenced here has been accomplished under relatively low stress levels. One can't help but wonder what the effects of high stress levels due to life threatening situations such as aircraft or battlefield emergencies will have on speech recognition accuracy.

These researchers plan to continue to document the effects of stress on speech recognition. As they do, the challenge will become one of finding ways to reduce these effects. This will be extremely difficult. Although it has been shown that training and using the recognition system under corresponding stress conditions improves performance, this appears to be impractical if not impossible for aviation applications. It would mean that each aviator would have to train the recognizer with the entire vocabulary under many levels of stress, assuming that the many levels of stress could be anticipated and duplicated. Another method being proposed is to automatically update training samples as the system is being used (14). Each speech input not only operates the system but also provides the system with an updated sample of the user's current speech patterns. This technique may be useful in those situations where the voice is experiencing a gradual change over time. For example, during the course of a day as the voice changes as a result of fatigue or the mouth becoming dry. This technique will probably not be effective for sudden changes in the voice due to unexpected stressful emergency situations.

At the moment, the change that occurs in the speech signal due to psychological and physiological factors appears to be one of the major impediments to the successful application of speech recognition technology in the LHX.

Speaker Variability

In the previous section, we discussed the changes that may occur in an individual's speech due to stress or fatigue.

Speaker variability refers to the differences in the speech patterns ng individuals. The cultural and geographical background of individuals affects the way they speak. Different parts of the country produce varying accents and rates of speech. Also, physical attributes such as vocal tract size create differences in speech. As mentioned previously, these differences among individual speakers are the major obstacle to speaker-independent recognition systems which allow anyone to use the system without having to first train the system. However, variability among speakers also presents difficulty for <u>speaker-dependent</u> recognition systems. For reasons that are not totally or clearly understood, speech recognition systems perform better with some individuals than they do with others. Results of speech recognition research are usually reported in terms of average accuracy rates or average error rates. Naturally, there is a range of performance that falls above and below the average performance. For example, in one study the recognition accuracy rate was reported at 95 percent; but for some test subjects (pilots), recognition accuracy was as low as 88 percent. In another study using pilots as test subjects, recognition accuracy ranged from 99 to 70 percent. The point is that there is a broad range of speech recognition performance due to speaker variability. For speech recognition to be viable for the LHX, it must be usable by all pilots, not just some pilots.

Protective Masks

In view of the enemy chemical warfare threat, it is likely that Army aviators may have to wear chemical protective masks in flight. The US Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, conducted a laboratory experiment to determine the impact on speech recognition when speaking through a protective mask (13). Twelve Army aviators tested the performance of a speech recognition device using the standard helmet-mounted M87 microphone, the M24 aviator protective mask, and the XM33 developmental protective mask.

The M24 mask is the standard mask currently used by Army aviators. The microphone is mounted inside the mask directly in front of the mouth. The XM33 is a prototype developmental mask. The microphone is mounted behind the diaphragm outside the mask, and the voice is emitted through a flapper valve to the microphone.

Recognition accuracy rates were 92 percent with the M24 mask, 88 percent with the helmet-mounted microphone, and 85 percent with the XM33 mask. While this performance is not acceptable for an operational aircraft, it is encouraging that recognition performance when speaking through the chemical protective masks was no worse than that when speaking through the standard helmet-mounted microphone. It does not appear that the use of protective masks will present any special problems for speech recognition in the cockpit. As a matter of fact, masks with the microphone mounted inside, such as the M24, attenuate noise and may even enhance performance in a noisy environment.

Speech Generation Issues

Computer generation of speech is not as difficult to achieve as computer recognition of speech. Speech generation technology is sufficiently advanced for use in aircraft today. The human factors issues of speech generation technology may be considered in the category of optimizing its performance and effectiveness in the cockpit as opposed to the more critical issues associated with speech recognition.

As mentioned previously, computerized voiced messages can be generated either by digitizing messages produced by a human speaker or by synthesizing speech electronically. The advantage of digitized human speech is its high quality and intelligibility. The disadvantage of this technique is that the storage of the digitized messages consumes a lot of computer memory space. This is especially a disadvantage where space and weight considerations are extremely important. Synthesized speech does not require large amounts of computer memory. Each entire message is not stored in memory. The approximately 40 basic sounds that make up the English language are stored in memory and are formed into words using linguistic principals and rules. Using synthesized speech, it is easier to modify messages. Until recently, the disadvantage of synthesized speech has been its poor speech quality and general unintelligibility. A speech synthesis system has recently been marketed that provides speech quality and intelligibility that approaches that of digitized human speech. The advantages of synthesized speech make it the likely candidate for the LHX.

Research is being conducted to determine whether a male, female, or "robotic" type voice is more effective in providing cockpit warning messages (5, 9, 15). The development of optimum message formats is also under study (18). These efforts will serve as the basis for future design guidelines for cockpit voice warnings.

Information Feedback

Ideally, voice technology will be used interactively. When the pilot uses speech recognition to command an operation, select a function, or request information, some type of feedback acknowledging that the system has responded must be provided. This feedback may be visual information appearing on a video screen or auditory information presented through the headset by speech generation. For example, the pilot may request the distance to the next waypoint. The distance could be provided visually on a display or aurally through the headset. If the motive for employing voice technology in the cockpit is to provide the pilot with more visual free time for "out-the-window" tasks, then the auditory presentation would seem preferable.

Researchers at the US Army Aeromechanics Laboratory, National Aeronautics and Space Administration - Ames Research Center, Moffett Field, CA, addressed this issue in a laboratory experiment (20). Nonpilot test subjects were tested on a computer graphic simulation of flight in which a helicopter symbol was maneuvered through a maze of obstacles displayed on a video screen. Information on airspeed, altitude, and torque (power setting) was necessary for optimum performance on the task. These parameters were presented with either conventional dial gauges, a heads-up display located on the video screen around the maze, or a speech synthesis system. Analysis of the results indicated that there was a significant difference in the test subjects' ability to negotiate the flight maze depending upon the method of information presented. Performance was best when using speech synthesis followed by the heads-up display. The worst performance was experienced when using the dial gauges.

These results tend to support the notion that auditory feedback of information provides more visual free time for flying the helicopter. However, certain information, such as complex or lengthy information messages or messages that must be referred to over time, may be better suited for visual presentation.

It is important that information feedback be tailored and integrated so that it is presented to the pilot in the form that will be most effective in reducing his workload and enhancing his performance. This may require some combination of visual displays, with critical information preferably presented on the same display through which the pilot is observing the "outside world," and a speech generation system.

SUMMARY AND CONCLUSIONS

It appears that there is potential for voice technology to reduce workload and enhance pilot performance in future Army helicopters, thereby increasing combat effectiveness and minimizing combat losses. At the present time, it is not evident that voice technology can fulfill this potential.

The implementation of speech generation in an LHX aircraft should be a relatively simple task when compared with speech recognition. Current state-of-the-art technology is capable of providing voice messages in an aircraft environment. There are some questions concerning computer memory available to meet the requirements of digitized speech and the intelligibility of synthesized speech. There are also questions regarding whether a male, female, or computerized voice should be used. However, these questions appear to be solvable; and speech generation systems are considered to be feasible and practical for the LHX.

As described in this report, speech recognition is more difficult to achieve than speech generation. It is apparent that some critical issues need to be resolved for speech recognition to be a viable technology for the LHX. The National Research Council, under the sponsorship of several government agencies, recently completed a study of speech recognition in severe environments (8). This study points out that:

> Current speech recognition technology is fragile; that is, recognizer performance, which can often be demonstrated favorably in the laboratory, may degrade

significantly under the effects of acoustic noise, user stress, and operational conditions. Thus, recognition depends not only on detailed system specifications but on a myriad of subtle factors as well. In the laboratory, speaker-dependent, isolated word recognition systems often can recognize up to 100 words with about a 1-percent error rate, but the performance of operational systems often falls far short of this. Extension to speaker independence, connected words, difficult vocabularies, or noisy/stressful environments may increase error rates even more.

It is a challenge to propose that a speech recognizer be used in a noisy helicopter by a large number of speakers with individual differences who may be experiencing various levels of stress and fatigue and achieve 99 percent recognition accuracy rates. Current state-of-the-art speech recognition technology has not demonstrated that it can meet the rigorous demands of the cockpit environment of today's helicopters.

The conclusions of the National Research Council were:

1. The use of speech for communication between humans and machines (automatic recognition for input, automatic synthesis for output) has distinct

potential for aiding humans in the acquisition, organization, and processing of information.

2. Current technology for automatic speech recognition-- including algorithm development, hardware design, and human factors integration--is not sufficiently advanced to achieve robust, reliable performance in hostile and high-stress environments.

3. Current technology is not sufficiently advanced to achieve high performance in applications where large vocabularies and/or continuous spoken input are needed, and where the ability to understand speech from a wide variety of speakers is required, even in benign environments.

4. Current technology is, however, mature enough to support restricted labor-saving applications in benign environments, with disciplined use under low-stress conditions. The success of these and of future applications depends on the integration of speech recognition with related automation techniques. With the exception of several

experimental data bases, no systematic, standardized techniques exist for evaluating and comparing the performance of speech recognizers.

5. No established human-factors methodologies exist that specifically differentiate the benefits of speech input from related automation techniques. Neither are there methods that reveal the optimum human-machine architecture for integrated voice systems or set requisite performance levels for speech recognizers embedded in prescribed operational tasks.

If there is room for optimism, it is the fact that the three military services and the National Aeronautics and Space Administration are all intent in pursuing voice technology for airborne applications. The response of those vendors who are producing speech recognition systems for "severe" environments is also encouraging. Through these efforts, it may be possible that the problems currently facing speech recognition technology can be overcome. Assuming that the issues can be resolved, the question remains, "Can they be solved in the LHX acquisition time frame?" This question is impossible to answer because one cannot predict "breakthroughs" that may occur.

Although the limited use of speech recognition may be feasible in early LHX aircraft, it appears that the extensive use of speech recognition for time or task critical functions must be considered a high technology risk for full-scale development in 1987.

In view of the potential utility for speech recognition to enhance pilot performance and facilitate single-pilot operations, it is important that efforts continue to improve speech recognition performance and to accelerate its development so that it may be extensively used in helicopter cockpits as soon as possible. Highest priorities should be given to the development of speech recognition algorithms that are not affected by speech variations due to stress and to speaker variability.

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ANNEX R-VII

ISSUES FOR A TRADE-OFF ANALYSIS OF CONVENTIONAL VERSUS ADVANCED COCKPIT CONTROLLERS FOR THE LHX

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Annex VII to Appendix R

ISSUES FOR A TRADE-OFF ANALYSIS OF CONVENTIONAL VERSUS ADVANCED COCKPIT CONTROLLERS FOR THE LHX

R-VII-1. Reproduced on the following pages is the report: "Issues for a Trade-Off Analysis of Conventional versus Advanced Cockpit Controllers for the LHX."

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ISSUES FOR A TRADE-OFF ANALYSIS OF CONVENTIONAL VS. ADVANCED COCKPIT CONTROLLERS FOR THE LHX

1. Introduction

The purpose of this paper is to present some key issues which must be resolved in a selection of primary cockpit controllers for the LHX and to provide background information necessary for the trade-off analysis required to resolve them. Primary controllers are those "used by the pilot to continuously modify the movement of the aircraft" (1). For the purposes of this paper, "conventional" controllers are those found in current helicopters, that is, longitudinal and lateral cyclic stick, collective stick, and directional pedals. "Advanced" controllers are only advanced in the sense that their design is not constrained by mechanical control system characteristics; it is assumed throughout this paper that the LHX is equipped with a fly-by-wire or fiberoptic flight control system. This assumption implies that the pilot's primary controllers are not mechanically connected to the rotor control actuators or other control devices and, as a result, gives the designer a significant amount of freedom to tailor the controller characteristics to the pilot.

Much of the background information presented herein is based upon investigations of the effects of controller characteristics on aircraft handling qualities: "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role" (1). Handling qualities are therefore influenced not only by aircraft stability and control characteristics but also by factors such as the design of the cockpit interface - the controllers and displays provided for the required tasks. All of these handling qualities studies have assumed a two-crew situation; no duties such as navigation, communication, and battle captain functions, which would be performed by the pilot of a single-crew LHX, were assigned to the pilots. Extrapolation of these results to the single-crew situation must therefore be based upon sound engineering and piloting judgment.

The controller tradeoffs addressed in this paper are: 1) conventional vs. side-stick controllers, 2) displacement vs. force controllers, and 3) separated vs integrated controllers.

2. Conventional vs. Side-Stick Controllers

Cockpit Design Implications

The replacement of the conventional set of primary controllers by a single side-stick controller can yield significant benefits. An increase in available cockpit real estate provides valuable room for the additional avionics required to perform the LHX SCAT mission. In a comparison of conventional cockpit controllers with a configuration consisting of a two-axis side-stick and small-displacement collective and pedals, Ref. 2 reports a 30% weight savings with the side-stick configuration. This same study claims significant improvements in both flight safety and mission reliability with the advanced controllers.

Certain human factors and man-machine integration benefits can also be derived from a cockpit design which employs a side-stick controller. Potential benefits include improvements in : 1) visibility, due to the removal of the pedals and cyclic stick; 2) ingress and egress, especially if the side-stick can be mounted on a movable armrest as in Ref. 3; 3) crashworthiness, due to the removal of potentially lethal objects from the cockpit; and 4) pilot comfort, by eliminating the need for the traditional helicopter pilot slouch over the controls and by allowing feet-on-the-floor flight. However, "any benefits gained in a substantial deviation from this (conventional) arrangement must be weighed against the costs of retraining the pilot's spontaneous control command patterns, particularly in high workload and emergency situations" (4).

Feasibility Studies

Simulator and flight investigations have demonstrated the feasibility of the use of a side-stick controller in both fixed- and rotary-wing aircraft for certain tasks. All of the fixed-wing studies involved side-sticks with two axes of control: pitch and roll. In a 1957 NACA-sponsored program, a Navy F9F was equipped with a side-stick controller to investigate the control implications of such a device (5). All of the pilots were able to execute precision flying tasks with no performance degradation. Pilot effort was felt to be reduced because of the lighter control forces and the comfort provided by the controller armrest. In 1970, the Air Force Test Pilot School flew an F-104 equipped with a side-stick controller (6). The side-stick was unanimously preferred to the conventional center stick and provided superior trajectory control with drastically reduced pilot workload. Over 60 pilots flew with the side-stick and accumulated 870 hours of flight time with no controller failures. A direct comparison of pilot performance with a center-stick and a side-stick was performed at Wright-Patterson AFB in 1970 (7). The study concluded that a side-stick was feasible for use in high speed, high altitude maneuvering tasks, resulted in improved performance for landings and other precision maneuvers, but yielded degraded performance for large-amplitude maneuvers at low altitudes.

Feasibility studies of the use of side-stick controllers in helicopters began in 1968 with the Tactical Aircraft Guidance System (TAGS) program (8). That system was implemented in a CH-47B aircraft and initially included a four-axis displacement controller; because of anatomical coupling problems between the longitudinal and vertical axes, a three-axis controller was eventually implemented with vertical control effected through a standard collective lever. Pilots were also critical of the longitudinal control implementation; the large displacement (4.5 inches) and viscous damping created a controller which felt massive and heavy. Both the lateral axis (a base-pivot design) and the directional axis (a twist-grip) were considered acceptable. The use of multi-axis controllers was rejected for the Heavy Lift Helicopter (HLH) primary flight control system (9); however, a four-axis finger-ball displacement controller was implemented at the load-controlling crewman's station in that vehicle for precision cargo handling tasks requiring a high level of stability and control augmentation.

In a three degree-of-freedom moving-base simulation of the unaugmented Lynx helicopter at RAE Bedford, a two-axis displacement side-stick was compared with the conventional cyclic controller for 11 different flight tasks (10); when a suitable control sensitivity was selected, the side-stick compared favorably with the conventional controller and, in fact, was preferred for certain of the tasks which required only small control movements. Manual trimming was considered to be difficult because of the trim button location and the force required to operate it; inadvertent control inputs were the result. A simple armrest drew no adverse comments, but a wrist support was recommended. In a piloted simulation of an Advanced Scout Helicopter (ASH), an A-7/F-16 two-axis side-stick was found to be feasible for an ASH mission when employed with suitable levels of stability and control augmentation (2).

A feasibility study of a four-axis isometric (rigid) side-stick controller was conducted in the Canadian National Aeronautical Establishment Airborne Simulator, a variable stability Bell Model 205A-1, for a wide range of flight tasks (11). Two primary side-stick configurations, a four-axis controller and a three-axis controller with normal pedal control, were evaluated together with variations in the level of stability and control augmentation. A conclusion of this study was: "It is clear from these experiments that a helicopter can be flown through a wide range of visual and instrument flight tasks using either a three-axis or four-axis isometric side-arm controller-without requiring exceptional pilot skill or concentration and within the bounds of normal helicopter work load demands". In a follow-on flight investigation (12), a comparison of conventional controllers with the same two isometric side-stick configurations was conducted by flying the Airborne Simulator with augmented pitch, roll, and yaw rate damping through a low-altitude course involving both maneuvering and precision flight. For this experiment, "the pilots generally considered isometric (side-stick) control to be more difficult and less precise, in this type of closely bounded task, than conventional control".

Handling Qualities Studies

Handling qualities studies-those which elicit both Cooper-Harper pilot ratings (1) and pilot commentary-which compare conventional controllers with side-stick controllers are rare. The Ref. 11 flight investigation revealed that, with appropriate gains, shaping and prefiltering applied to the pilot's force input in each controlled axis, pilot ratings comparable to those obtained with conventional controls were achieved by both primary side-stick configurations (12). In two moving-base simulations of helicopter visual terrain flight (13), it was determined that the employment of a properly-designed two-axis displacement side-stick controller could, in fact, improve handling qualities over those provided by conventional controllers but that increased levels of stability augmentation were required to achieve comparable pilot ratings if a three- or four-axis isometric controller was employed.

Summary

The use of a single side-stick controller to replace the conventional set of helicopter controllers offers significant advantages to the cockpit designer and has the potential for enhancing pilot safety and comfort. However, based upon the results of the feasibility and handling qualities studies cited in this section, a single, multi-axis side-stick controller has never been demonstrated to improve handling qualities for any helicopter flight tasks; in fact, there is a strong indication that increased levels of stability and control augmentation are required to achieve even comparable handling qualities for visual terrain flight tasks similar to those required of the LHX SCAT. Only a properly-designed two-axis side-stick has been shown to offer the potential for improved handling qualities compared to a conventional cyclic stick; it is very possible, however, that improved conventional cyclic stick force characteristics would negate, or reduce the significance of, this advantage.

3. Displacement vs. Force Controllers

Input Bandwidth

With a conventional set of controllers, the position of each controller with respect to some reference point is the pilot's input to the control system. To produce the desired control input the pilot must apply the control forces required to accelerate the controller to some velocity and then to decelerate it to zero velocity at the required position. The use of a force controller brings the pilot two integrations closer to the control of the flight path of the aircraft since the applied force is itself the input quantity. As a result, the inputs seen by the control system could have a much higher frequency content, or bandwidth, than when displacement controllers are employed. This characteristic provides the potential for a more precise control of the flight path but also makes the control system, and hence aircraft response, more sensitive to sharp pilot inputs, inertial forces such as those experienced in high-g maneuvers, and aircraft vibrations fed through the controller grip. It was for these reasons that the original force-sensing stick of the F/A-18 was replaced by a displacement controller during full-scale development testing (14). In that program, forward path prefilters were employed in the digital flight control system to smooth the pilot's inputs from the force stick but also resulted in degraded controllability. Extra weight was required to mass-balance the stick against the forces caused by catapult launch. Notch filters in the flight control software were required to prevent structural interaction through the inertia of the grip and pilot's arm at structural resonance frequencies; these filters also caused additional time delays which further degraded handling qualities and caused pilot-induced oscillations.

Advantages and Disadvantages

The advantages of a force controller lie in its inherent simplicity, reliability, and low parts count (3). In addition, no force feel system is required to provide the control force characteristics dictated by handling qualities requirements. However, the lack of explicit control position information from a force controller can be a significant disadvantage. Although the human pilot is not a particularly accurate sensor of controller displacement, the lack of any displacement cues can degrade the ability to make smooth and precise control inputs. An operational problem caused by this lack of control position information was highlighted in the Refs. 11 and 12 flight experiments. The analogies between conventional cyclic stick position and main rotor tip-path plane orientation and between pedal displacement and yaw control authority remaining, both so important in certain flight regimes, were eliminated because of the use of the force controller; the former relationship is particularly important for slope takeoffs while the latter provides important information when operating with large yaw rates or in the presence of large sideslip angles. A visual presentation of this information was provided on the instrument panel to compensate for the loss of control position cues. Problems due to the lack of absolute collective pitch angle information were revealed in simulations conducted to support the JVX development. During takeoffs, autorotations, or maneuvers at high power, conventional collective stick position, as an analog for collective pitch angle, provides important information to the pilot; as a result, the original force controller used for vertical control inputs was replaced by a small displacement controller.

Because of the lack of motion of a pure force controller, both trimming and, in a two-pilot situation, control transfer become more difficult to implement. With a sophisticated flight control system the need for manual trim inputs may be eliminated by incorporating automatic trim logic in the control laws. Similar logic may be incorporated to assist in control transfer to minimize aircraft transient response. However, in situations with a degraded flight control system, trimming and control transfer may have to be performed unaided. Low-force trim switches are required to eliminate the possibility of inadvertent control inputs while trimming; in addition, the rate of removal of steady trim forces must be carefully selected to minimize any transients.

In a related area of concern, any secondary control functions or selectors mounted on the grip of a force controller must be implemented so as to minimize any hand motion or application of force which might cause inadvertent primary control inputs. Low-force switches or buttons are a requirement with a force controller.

Results of Force/Deflection Studies

Results of both fixed- and rotary-wing handling qualities research to investigate the relative benefits of force and displacement side-stick controllers indicate significant advantages for limited-displacement controllers. In several fixed-wing flight investigations typified by Reference 15, an "optimum" region for force-deflection relationships was defined for two-axis side-stick controllers. Typically, isometric force controllers yielded performance which was very sensitive to the control sensitivity (aircraft response per unit of applied force) provided; adequate performance was only possible for a very restricted range of control sensitivities. As the amount of controller compliance increased, the region of acceptable control sensitivities also increased to some maximum value.

With further increases in controller deflection-per-unit-applied-force, degraded handling qualities occurred with comments about excessive stick motion requirements and overshoots in aircraft response. The results of these flight experiments were incorporated in a design guide for two-axis side-stick controllers used in fighter aircraft (16). Aircraft design experience also substantiates the limited-displacement requirement. The original side-stick design for the F-16 prototype incorporated a virtually zero displacement force controller (±0.030 in at the grip); subsequent refinement for the production F-16 showed that a ±0.2 in displacement was desired for longitudinal control and a ±0.10 in displacement was desired for lateral control.

A total of seven different four-axis side-stick controllers, exhibiting a wide range of force-deflection characteristics, was evaluated for use in helicopter terrain flight during the ADOCS Advanced Cockpit Controls/Advanced Flight Control System (ACC/AFCS) simulator investigations (17-19). It was found that, as in the fixed-wing investigations, the introduction of a limited amount of deflection in the pitch and roll axes yielded improved task performance and handling qualities. Too much deflection resulted in comments on sluggish control response and less precise attitude control. Harmony among the four control axes was also an important consideration; a controller with two limited-deflection control axes (pitch and roll) and two rigid control axes (vertical and directional) was judged to be only marginally acceptable. All pilots felt that deflection in all control axes improved the ability to modulate single-axis forces, produced less tendency for overcontrol and anatomical coupling, and enhanced control precision for high-gain piloting tasks such as precision hover.

To compensate for the potential of an increased control input bandwidth with a force-sensing controller, both the ADOCS and Canadian (20) side-stick implementations included some pre-processing of the control force input before it was used to drive the control systems. A non-linear shaping function, consisting of a dead zone (or breakout) and quadratic (Canadian) or piecewise-linear (ADOCS) control sensitivity function, was employed to provide acceptable levels of control sensitivity about zero force with minimum coupling of control inputs while permitting large, short duration inputs to be made without excessive control force. In addition, to guard against the response of the aircraft to sharp pilot inputs such as the rapid release of large control forces, both systems incorporated techniques to smooth the control input. The Canadian system employed a 16 rad/sec first order filter in each control axis while the ADOCS control laws included a "derivative rate limiter" designed to limit peak accelerations for large control inputs without affecting control precision for small force inputs.

Summary

A summary of the advantages and disadvantages of a force-sensing controller is presented below:

ADVANTAGES	DISADVANTAGES
High control input bandwidth	Susceptible to sharp pilot inputs, inertial forces, vibratory inputs
Simplicity	Lack of control position information
Reliability	Manual trimming and control transfer more difficult
Low parts count	Low-force buttons and switches required to prevent inadvertent inputs
No force feel system required	

Small-displacement force controllers have been shown to provide significant handling qualities advantages over rigid controllers. However, the control system software employed with this type of controller must include means to compensate for sharp pilot inputs and vibratory forces and to provide the capability for trimming, both automatic and manual, and, in the two-crew situation, control transfer. Low-force buttons and switches are required for any grip-mounted secondary controllers or selectors. The lack of explicit control position information may very well be a problem under operational conditions such as slope takeoffs or flight with large sideslip angles and emergency conditions such as engine and flight control system failures.

4. Separated vs. Integrated Controllers

For the purposes of this discussion, fully "integrated" controllers are those which combine all primary control functions on a single device. "Separated" controllers are produced when one or more of these functions is removed from the integrated controller. Levels of integration evaluated in both the ADOCS and Canadian investigations range from a fully-integrated four-axis device to a separated controller configuration consisting of a two-axis side-stick and conventional collective and pedals. Two primary issues are discussed in this section: 1) human factors requirements for controller integration and 2) handling qualities effects of the level of integration.

Human Factors Requirements

Three "human factors" requirements related directly to the integration of multiple control axes on a single controller are discussed: the selection of an appropriate controlled axis reference system, grip design requirements, and compensation for human pilot characteristics in both hardware and software.

A number of two- and three-axis hand controllers have been investigated for fighters, spacecraft, and helicopters. These controllers have used a variety of reference systems for the control inputs. The roll control axis has been parallel to the forearm and beneath the hand in almost every controller tested With this roll axis, the most intuitively correct pitch control axis is horizontal, perpendicular to, and intersecting, the roll axis. This axis system, used for the conventional center stick and the F-16 side-stick, requires some forearm motion for pitch inputs to a displacement controller, a possible disadvantage in a high-g or vibratory environment. As a result, other pitch pivots which allow operation without arm movement, such as wrist- or palm-pivots, have been investigated. Both the ADOCS and Canadian research programs employed a more classic base-pivot set for pitch and roll to minimize the risk inherent in a transition to a side-stick controller. The yaw axis of control in a hand controller has been implemented in several ways; the most prevalent has been the grip twist about the vertical axis of the hand grip itself. Alternatives, such as a thumb lever to avoid the input cross-coupling problems inherent in the grip twist approach, result in hand fit problems and pilot fatigue To maintain control input-aircraft response compatibility, vertical control was effected through the application of pure up and down forces in both the ADOCS and Canadian programs; a configuration evaluated by the Canadians using grip twist as the vertical input was confusing and unacceptable.

Much more stringent requirements for grip design exist for integrated controllers than for separated, conventional controllers. The grip must be shaped so as to assist the pilot in identifying the controlled axes by providing a constant hand position with respect to the grip. It must be designed to allow the pilot to make clean control inputs into each axis with a minimum of inadvertent inputs into other axes. The original hand grip, supplied with the isometric controller evaluated by the Canadians, was found to cause vertical-to-pitch and roll-to-yaw input cross-coupling; a redesigned grip was found to be more acceptable (12). This new grip formed the basis for the design of the integrated controller grip being implemented in the ADOCS demonstrator helicopter.

Other design factors, while important for separated controllers, become critical for integrated controllers. The controller location, orientation, and armrest/wrist support design are crucial factors in determining the pilot's ability to make smooth, uncoupled control inputs with a minimum of effort and maximum comfort. The ADOCS program has supplied a significant number of lessons learned in this regard. Finally, to compensate for relative arm/armrest/ controller geometry effects, it may be necessary to provide asymmetric control sensitivities in certain control axes. For example, the Canadian program revealed that it was significantly easier for the pilot to produce an upward vertical force than a downward force using the four-axis controller configuration; a larger value of control sensitivity in the downward direction was provided as a result. Additionally the ADOCS program provided a higher control sensitivity in the yaw axis for a clockwise directional input than for a counter-clockwise torque to compensate for a similar human asymmetry.

Handling Qualities Effects of Controller Integration

A significant handling qualities data base has been created to substantiate an interactive effect which must be assessed during the LHX trade-off analysis: the interaction between controller integration and level of stability and control augmentation. In general, for a given piloting task, increasing levels of controller integration must be accompanied by increasing levels of stability and control augmentation to ensure that performance and handling qualities do not degrade. In the ADOCS ACC/AFCS simulations, it was found that controller configurations which included a separated vertical controller - with either a three- or two-axis side-stick - exhibited handling qualities which were generally improved compared to the integrated four-axis controller configurations for the lower levels of stability and control augmentation investigated. Separation of the vertical controller eliminated any inadvertent coupling of control inputs from the vertical to the pitch or roll axes and reduced pilot workload for multi-axis tasks such as NOE maneuvering. For the higher levels of stability and control augmentation investigated, handling qualities were less affected by the level of controller integration; there was a general preference for side-stick rather than pedal control of the yaw axis, despite a tendency to couple yaw inputs into the roll axis, because of the precise directional control which could be achieved with a hand controller.

In a four flight-hour "validation" of the ADOCS simulation results for the lower levels of stability and control augmentation conducted in the Canadian Airborne Simulator, Boeing Vertol pilots found that many of the simulation results were substantiated by the flight evaluation. Pilot comments indicate that the integrated four-axis side-stick created high workload and degraded flight path performance especially during the multi-axis maneuvering tasks. The three-axis controller which incorporated pitch, roll, and yaw control on the side-stick was the preferred controller configuration because of the decoupling of vertical control inputs and improved directional control. With all stability and control augmentation removed, a fully separated controller configuration was required to perform a decelerating approach to hover and landing; the four-axis configuration resulted in an uncontrollable aircraft for this task. Pilots indicated that they would have preferred conventional displacement controllers for landing the aircraft in this condition.

From the handling qualities investigations conducted in flight by the Canadians, it is apparent that integrated controllers are certainly feasible and do not degrade aircraft handling qualities when compared to conventional controllers for non-precision tasks such as cruise flight and maneuvering at altitude. However, for precision flight tasks and high workload situations such as encountered in NOE flight, the ADOCS simulation studies and limited flight validation results indicate that, unless high levels of stability and control augmentation are employed, integrated controllers can cause significantly degraded handling qualities compared to separated controller configurations.

A single, integrated controller may be a requirement for a single-crew LHX SCAT in order to allow the pilot to perform the other supervisory and control functions required during the mission. Accordingly, an experiment was conducted to investigate the use of multi-axis side-stick controllers for flight path control together with a keyboard entry task using the free hand (21). The results show that keyboard entry tasks interfere with the performance of flightpath tracking and, conversely, that flightpath tracking interferes with keyboard entry. If a degradation in performance occurs, the use of a multi-axis controller to free a hand for mission management tasks may not be appropriate.

Summary

Flight and simulation studies have shown the feasibility of using properly-designed limited-displacement, integrated controllers for certain relatively routine flight tasks in two-crew rotorcraft with nominal levels of stability and control augmentation. However, for the more demanding flight tasks typical of the LHX SCAT mission, unless high levels of stability and control augmentation with a high degree of reliability are incorporated, separated controller configurations are required for acceptable handling qualities.

5. Concluding Remarks

This paper has highlighted several significant advantages of employing a limited-displacement, integrated side-stick controller in certain areas, including human factors and man-machine integration issues such as improved visibility, ingress/egress, crashworthiness and pilot comfort. However, in order to provide acceptable LHX handling qualities with an integrated controller, high levels of stability and control augmentation with a high degree of reliability are required; flight control or propulsion system failures may cause this acceptable aircraft to become uncontrollable.

Design criteria which include pilot-oriented requirements are crucial in the development of an acceptable integrated controller configuration. Details such as controller location and orientation, armrest and wrist support design, and grip design including buttons and switches, important for conventional controllers, are critical for integrated, limited-displacement, force-sensing controllers. An equally important set of design criteria involves the flight control system software employed with the controller; the characteristics of the control input pre-processing and the type of stability and control augmentation system have a dominant effect on the suitability of a particular controller. As with many other aspects of LHX cockpit design trade-offs, an effective analysis of controller issues must be based upon an integrated application of principles and guidelines employed by several communities including pilots, avionics engineers, engineering psychologists, control engineers, and human factors specialists.

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ANNEX R-VIII

BIOMEDICAL ANALYSIS OF VISUAL DISPLAY AND COCKPIT DESIGN OPTIONS FOR THE LIGHT HELICOPTER FAMILY (LHX)

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Annex VIII to Appendix R

BIOMEDICAL ANALYSIS OF VISUAL DISPLAY AND COCKPIT DESIGN OPTIONS FOR THE LIGHT HELICOPTER FAMILY (LHX)

R-VIII-1. The report, "Biomedical Analysis of Visual Display and Cockpit Design Options for the Light Helicopter Family (LHX)" is reproduced on the following pages. The report was the result of research and investigation conducted by the Sensory Research Division of the U. S. Army Aeromedical Research Laboratory of Fort Rucker, Alabama.

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BIOMEDICAL ANALYSIS OF VISUAL DISPLAY AND COCKPIT DESIGN OPTIONS FOR THE LIGHT HELICOPTER FAMILY (LHX)

by

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SENSORY RESEARCH DIVISION

October 1984

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R-VIII-5

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INTRODUCTION

As part of the concept development phase for the Light Helicopter Family (LHX), the Directorate of Combat Developments (DCD), US Army Aviation Center, Fort Rucker, Alabama, requested that the US Army Aeromedical Research Laboratory (USAARL) provide input for the LHX Trade-Off Analysis (TOA). This input was to be based solely upon LHX design options as presented in the LHX Trade-Off Determination (TOD). DCD requested that only qualitative summaries, conclusions, and recommendations be provided rather than a full quantitative research assessment. The following qualitative analyses present potential health hazard and visual physiology issues and operator workload issues with respect to the LHX cockpit design and visual display options as given in the TOD. Technical references and discussions have been kept to a minimum in order to make the issues clearer for a nontechnical audience.

This report is organized into four major sections. The first section presents a summary of the qualitative analyses of health hazards and visual physiology issues with respect to visual displays for the LHX. The second section presents a summary of the qualitative analyses of operator workload within the LHX, specifically with respect to whether the LHX should be designed with a one- or two-person cockpit. The third section presents conclusions and recommendations with respect to the LHX workload analyses. The final section presents the implications for research and outlines where quantitative research assessment may have to be conducted to resolve some LHX design issues.

HEALTH HAZARD AND VISUAL
PHYSIOLOGY ASSESSMENT

Potential health hazards and performance decrements were assessed with respect to the panoramic display concept, visual display hardware options, and the Advanced Aircrew Integrated Helmet System. These analyses were based upon known and/or recurring health hazard issues in Army aviation, applicable USAARL laboratory reports, and a brief review of the literature pertaining to visual physiology. A standard health hazard assessment analysis and report as outlined in AR 40-10 was considered to be inappropriate due to the request for a nontechnical qualitative assessment, lack of actual testing of equipment, lack of specific design parameters, and the conceptual nature of the trade-off analysis. Known or anticipated health hazards and visual performance decrements are summarized here by listing favorable and unfavorable aspects of the various design options. Brief discussions or reference citations are included where needed.

Panoramic Display Concept (Virtual Cockpit)

The panoramic display was described as a single display having a wide field of view (100 degrees horizontal by 60 degrees vertical) upon which all visual display information will be presented continually in addition to an unaided view of the outside scene. The favorable aspects of this concept are that fatigue from eye movement and eye refocusing may be reduced as searching for specific instruments and across variable visual formats will be minimized.

The intent of the panoramic display is to allow the pilot to maintain visual contact of the battlefield while still interacting with aircraft system displays. This avoids the requirement for the pilot to look 'inside' the cockpit for information, therefore briefly losing sight of the battlefield. However, superimposing the visual display information upon an outside scene will cause conflicts in visual attention. It has been demonstrated experimentally that in similar situations visual attention can focus either upon the display information or the outside view, but not both simultaneously (Haber and Hershenson, 1973; Kaufman, 1974). Should the pilot be concentrating on the outside view, significant changes in the visual display may be missed, and vice versa. This problem has been observed by USAARL investigators during training with the Integrated Helmet and Display Sighting System (IHADSS) in the AH-64 surrogate trainer at Ft. Rucker. The pilots had difficulty maintaining visual attention on the display as indicated by either closing the left eye or attempting to block out the background view in the IHADSS display. Air Force visual performance investigators have indicated that a display/background attentional problem occurs in the A-7 and other aircraft equipped with a head-up display, particularly under conditions requiring extensive use of the displayed information. However, there have been no formal attempts at outlining the parameters or investigating the seriousness of this display/background attentional problem using advanced symbologies and panoramic display advanced technologies. (Reducing pilot workload through the use of a panoramic display will be discussed in the second section.)

Mission Equipment Package (MEP)
Visual Display Hardware Options

A. Panel mounted displays: These types of displays were outlined in the MEP as multifunction display units that would be placed in a manner that would not obstruct the outside view. Cathode ray tubes (CRTs) currently constitute the primary technology available for panel mounted displays. The favorable aspects of CRTs include the capability for multicolor symbology, high resolution, high contrast, and flexibility in adapting to pilot display needs. Radiation should not be a health hazard. Numerous studies and reports have indicated that properly constructed CRTs are well below accepted safety standards for emission of both ionizing and nonionizing radiation at normal viewing distances (National Research Council, 1983; Wolbarsht, et al., 1980).

The unfavorable aspects of CRTs are:

1. CRTs may not be easily integrated with dynamic flight/weapon controls (i.e., visual coupling). Although head position sensing systems could probably be integrated with CRT technology, normal CRT viewing distance would introduce eye movements as a significant factor in determining where the pilot was looking at any given time. This could require eye position sensing for accurate visual coupling with CRT panel mounted displays.

2. A minimum of 7 inches diagonal measurement is the normally accepted size standard for normal CRT use (Woodson, 1981). However, CRT size is highly dependent upon viewing distance, display resolution, and the amount of information to be displayed. Resolution and contrast might become a problem in large CRTs.

3. Eye strain and fatigue sometimes have resulted from extended use of CRTs in administrative or word processing functions (DeGroot and Kamphuis, 1983; Grandjean and Vigliani, 1980). This may be due to the dynamic nature of the display information on CRTs (e.g., scrolling of text and screen flicker). It also may be due to excessive reading and general fatigue. However, eye strain and fatigue have not been tested for CRTs used in Army aircraft.

4. Various types of visual afterimage effects have sometimes occured after CRT use. These effects are dependent upon the type of phosphor used and the display intensity. The afterimages are of short duration and are not usually regarded as a severe problem. However, afterimage effects should be considered if CRTs are selected as a primary display tecnology.

5. Degraded contrast and poor display readability may occur due to glare from sunlight or other intense light sources.

B. Head-up displays (HUDs): This type of display would consist of a clear panel mounted in a head-up position upon which visual display information would be projected. The visual appearance is of superimposed images on the outside view. With respect to the pilot a large properly mounted HUD would subtend a large field of view for information presentation. The head-up position also would reduce search time and eye fatigue that could result from diverse or complex instrumentation.

An unfavorable aspect is that visual contrast, and therefore display readability, would be disrupted to some extent due to the highly variable background (i.e., the outside view) of the displayed information. For example, color and coding schemes that might produce high contrast with a forest background may not with an open field or sky background. Additionally, display/background visual attention disruptions, as previously discussed for the panoramic display, may result from using a HUD.

C. Helmet mounted displays (HMDs): These types of displays would be similar to the current Integrated Helmet and Display Sighting System (IHADSS) being used in the AH-64. The prototype HMD system as given in the Human Factors and MEP TODs consisted of a binocular HMD in order to implement a wide field of view virtual cockpit display system. This binocular HMD was suggested as the primary visual display system for the LHX. The present analysis concurs with the opinion given in the TOD that the binocular HMD has the greatest technological potential for meeting the display requirements necessary for the wide range of missions anticipated for the LHX. The favorable aspects of a binocular HMD are a large field of view, virtual elimination of eye search strain, visual coupling with flight/weapon controls, and the display of visual information in such a way to best promote situational awareness (to be addressed in the next section).

However, there are several unfavorable aspects that would be associated with the use of a binocular HMD. These are:

1. Variable contrast due to a changing background and display/background visual attention problems could affect visual performance in a binocular HMD. These issues were previously discussed.

2. The normal 20/20 field of view (i.e., where letters or other symbology can be recognized) when the head is stationary and only the eyes are allowed movement is aproximately 100 degrees horizontally. Therefore, a binocular HMD with at least a 100 degree horizontal field of view would maximize the area possible for usable information (i.e., symbology) display. However, a wide field of view for information display, such as 60-80 degrees vertically by 90-120 degrees horizontally, may no be sufficient for tasks highly influenced by information in the peripheral field of view. Efficiency and effectiveness of nap-of-the-earth (NOE) flying or air-to-air combat may be impaired because the pilot's peripheral field of view is restricted by the binocular HMD.

3. The weight and size of a helmet with binocular HMDs an head position sensors may unnecessarily fatigue or cause injury to the head/neck/shoulder areas. Power and interfacing cords may restrict head movement or cause neck/shoulder injury.

4. Visual afterimage effects may result from proximity of the visual display to the eye and the long-term continual display of visual information. This problem may be severe for HMDs as the pilot cannot 'look away' from the display device.

5. Current generation HMDs (IHADSS) do not pose a radiation hazard due to the low power voltages used in the projection CRT. Should these voltages be greatly increased (to meet some engineering constraint) radiation could become a significant health hazard, particularly due to the proximity of HMDs to the head and eyes.

6. A binocular HMD presenting a three-dimensional information display may interfere with normal depth perception of the outside view. This could degrade visual performance particularly in the case where the display depth does not match the outside view depth, creating the perception of symbology 'floating' in front of the outside view. Other interferences may occur in judging aircraft clearances (rotor and tail boom) or determining spatial orientation.

Advanced Aircrew Integrated Helmet System

The development of the Advanced Aircrew Integrated Helmet System (HGU-56/P) may have a large impact on both visual performance and health hazards in the LHX. Although development of this system already is underway, some brief comments are necessary.

The various laser, nuclear flashblindness, and chemical, biological, and radiological (CBR) protection systems to be included in this helmet must be compatible with whatever visual display technology is used in the cockpit. As discussed in the Human Factors TOD, the various visual protection and enhancement devices simply cannot be stacked in front of the eye. Doing so risks severe degradation of visual acuity, contrast, and color coding schemes. It cannot be assumed that a visual display system with advanced symbology and color coding will necessarily be compatible with laser, flashblindness, or CBR visual protection.

The number of protection systems proposed for the HGU-56/P may make the helmet quite cumbersome and heavy, particularly if HMDs also are attached. Neck fatigue and injury may be a problem. Reduced head mobility may occur from power and data cables attached to the helmet. Heat stress also may become a problem in long duration missions or under certain environmental conditions.

COCKPIT WORKLOAD ASSESSMENT

The advanced technological features and extended operational requirements of the LHX have forced the concept of pilot workload to be a significant factor in determining the cockpit design of the LHX. The design question is whether or not workload can be reduced sufficiently to allow one-man operation of the LHX within all anticipated mission scenarios. It has been suggested strongly in the Human Factors TOD that excessive pilot workload conditions will be present in both the one- and two-man cockpit configurations if the LHX is designed according to current state-of-the-art technology. Therefore, the present workload assessment concentrated upon the concept of workload in highly automated systems in order to determine whether the goal of workload reduction will be met by the program of system automation proposed in the Human Factors and Mission Equipment Package TODs.

The workload assessment proceeded through three stages: (1) a survey of the relevant man-machine interface design considerations as given in the TOD (Section F: Human Factors/Man Machine Interface; Section E: Mission Equipment Package; and LHX Mission Profiles), (2) a search of relevant literature addressing the issue of workload as it would be applied to the design considerations, and (3) an analysis of which design considerations would best meet the goals of reduced workload and address the one- versus two-man cockpit question. The following presents a final nontechnical summary concerning workload assessments of the various proposed automated systems and their anticipated functional relations to the pilot(s).

Definition of the Concept Workload

The concept "workload" has been used in many contexts as a means of expressing the idea that the human operator somehow is limited in his ability to perform in an optimum or efficient manner. There is no widely accepted theoretical definition of workload. High levels of workload are usually operationally determined through systematic errors or other performance decrements during some task or set of tasks.

The traditional human factors concern has been with errors and performance decrements resulting from the man-machine interface. The design questions of this type have revolved largely around information displays and system controls. Reduction in errors and improvements in performance have been obtained by redesigning the cockpit layout, changing the display symbologies, and making controls compatible with human operation.

An analysis of the professional literature in human performance limitations indicates that for highly automated systems the issue of workload not only includes the traditional concern of the man-machine interface, but also the use of the human operator in a managerial, or executive decision-maker, role in a significant fashion. That is, workload involves limitations in human memory, perception, decision making, and other aspects of information processing. Specifically, in automating aircraft capabilities, there is a shift from the pilot primarily performing skill-based functions to primarily performing knowledge-based functions (Hart and Sheridan, 1984; Rasmussen, 1983; Statler, 1984; Van Cott, 1984).

Skill-based functions roughly can be defined as analogous to riding a bicycle or driving a car. Once learned, the skill imposes relatively little workload upon the person (as opposed to, for example, watching the traffic or looking at store signs). Knowledge-based functions are decision making or management types of functions where the available information must be analyzed and a response strategy must be developed. Automated systems primarily release the pilot from skill-based functions and increase the role of the pilot in knowledge-based functions. That is, the pilot is now required to interact with "intelligent" machines (e.g., Hopson, Zachary, and Lane, 1981). However, humans are limited most in terms of what they effectively can accomplish within knowledge-based functions. That is, automated systems actually could increase pilot workload because the pilot's tasks have become more knowledge-based.

Panoramic Display

It was suggested in the TOD that some type of unitary panoramic display be used on which all visual display information will be presented. The purpose is to provide a means for displaying information in a head-up orientation to maximize situational awareness, the compatibility of the sensor information with actual battlefield conditions. The concept of the panoramic display is sound, and should enhance performance, although there is little in the professional literature that directly addresses workload reduction through the use of a panoramic display. However, care should be taken in the manner in which the panoramic display is implemented (apart from the display hardware used, as discussed in the previous section).

The effectiveness of promoting full situational awareness is highly dependent upon the situation. The necessary compression of information in order to accurately portray a complex battle situation in a single display would require very sophisticated coding and format schemes in order to avoid confusion and minimize readability problems. The human factors database is seriously deficient in outlining design guidelines for the display of procedural, factual, and structural types of information that are used by highly automated or artificially intelligent systems. A complex battlefield situation, even if presented in proper formats, remains a complex situation, and more cognitive information processing (knowledge-based functions) will be necessary to understand that situation.

Target Engagement/Fire Control

It was proposed in the TOD that the tasks of target detection, acquisition, identification, engagement, and handoff be automated. This will be the case for both ground target attacks and air-to-air engagements. The pilot will retain the tasks of target selection, fire commands, interpretation of targeting information, integration of targeting information and automatic threat analysis with mission needs and status, and evaluating manual override options. These are significant demands in terms of knowledge-based functions.

Navigational Systems

As determined in the TOD, hand-held maps produce unacceptably high levels of pilot workload. The critical workload factors are the map display method and how the pilot communicates with the system in order to input navigational parameters. Both digital numeric displays and projected map displays require high levels of knowledge-based deciphering and interpretive functions in order to understand the coded information presented in such displays. In addition, the navigational needs of the pilot differ depending upon whether flight is contour or NOE. Studies have shown that navigating has a very high visual workload component, even with navigational aids that improve overall flight and navigational performance (Cote, Krueger, and Simmons, 1982; Sanders, Simmons, and Hofmann, 1977).

Contour flight is more likely to be used in C^3 functions, combat service support, and flight to a combat station (as indicated in the LHX mission profiles). A graphic representation of aircraft position relative to terrain features, waypoints, destination, obstacles, and known enemy forces is needed. Navigational input could be accomplished by simply pointing to the location on the screen where the pilot wishes to go. Best flight path, necessary headings, speeds, and times can be calculated and displayed automatically relative to map features. However, the fashion in which this information is coded is critical in determining the effectiveness of the operator.

NOE flight is used in tactical combat scenarios where aircraft masking and surprise are mission requirements. The pilot needs information highly relative to his immediate surroundings. General headings and speeds may not be adequate nor account for small terrain obstacles. A digital display is required that presents real-time three-dimensional images based upon the visible terrain (or FLIR projection) where one can either fly through a "window" or follow some other marker through the terrain features. For example, the pilot could "fly" a symbol representing the aircraft through a set of obstacles presented on a CRT. The goal should be to release the pilot from the severe attentional demands of trying to maintain general headings through terrain obstacles. This should be done automatically.

The point being emphazised is that navigation must be automated to as large an extent as possible. The ideal system would perform all required navigation computations and display only the necessary heading and speed information in a way that minimizes interference with other tasks. This system also should be able to automatically determine and record enemy positions or other navigational data during scout missions.

Communications

Voice interactive control seems most appropriate for communications. The Integrated Avionics Control System (IACS) and the Integrated Communications, Navigation, Identification Avionics (ICNIA) outlined in the MEP require hands-on adjustments in order to select frequencies and type of radio. Voice control can be used to "tell" the communication system to set the necessary parameters for communication with a unit, aircraft, etc. However it is critical to develop the voice interaction so that a minimum of coding or verbal commands are required. Not much would be gained in workload reduction if the voice interactive system required verbal equivalents of hands-on functions.

Voice control and warning functions may produce some auditory interference problems. What happens if a verbal warning occurs while the pilot is conducting a critical radio communication? It is a well established fact that there are severe human cognitive limitations in attending to multiple sources of information through audition (Massaro, 1975, pgs. 259-319). Important changes in aircraft status or some critical information may be missed because the pilot was attending to some other auditory communication function.

System Status Monitoring

With the exception of critical flight parameters (e.g., attitude, altitude, heading, torque, air speed) there is little need to display any type of system status, nor involve the pilot in the monitoring or decision aspects of system status. System status most often involves the determination of when various systems of the aircraft are within acceptable operating levels. The proposed automated status monitoring system still requires the pilot to perform the knowledge-based functions of diagnosis and the determination of the necessary corrective action. The corrective action also must be implemented by the pilot. Pilot workload may increase if the monitoring system displays every unusual event or initiates warning signals in situations where the pilot cannot handle the necessary corrective decisions or actions. A simple multifunction display, while reducing the number of instruments in the cockpit, does not necessarily reduce the knowledge-based functional requirements, and therefore the workload, of the pilot (Statler, 1984).

Aircraft Survivability Equipment (ASE)

The increase in number and sophistication of countermeasure systems has the potential to produce a large increase in knowledge-based pilot functions. The present analysis concurs with the TOD recommendation that the ASE must be automated to as large an extent as possible. This means the pilot should not be included in any countermeasure decisions that can be accomplished automatically.

A secondary concern is the psychological impact automated ASE systems will have. Automation will be necessary in order to reduce workload, but will have the effect of removing survivability functions from the pilot's control. The psychological impact of not being able to easily intervene in order to save oneself may increase the anxiety that normally occurs during combat missions.

Aircraft Flight Control Systems

A significant point in the analysis of pilot workload is that the pilot still maintains flight control of the LHX aircraft. It can be argued that flight control is largely a skill-based function much the same as riding a bicycle or controlling a car is a skill. The implication is that automating flight control through stabilization systems or hover and hold systems may not necessarily reduce workload in a significant manner (e.g., Sanders, et al., 1978). The high workload in flight control occurs in watching for other traffic or following a specific route, which translates into either gross or precise levels of aircraft control and manuever depending on the flight profile. NOE flight is a particularly relevant example. The pilot must watch continually for and avoid small terrain obstacles and enemy action, thus forcing a high precision in the control and manuevering of the aircraft. Workload can be reduced and flight control improved by providing aids to these types of knowledge-based functional components of flight control.

COCKPIT WORKLOAD

CONCLUSIONS AND RECOMMENDATIONS

Anticipated pilot workload was evaluated with respect to the one- versus two-man cockpit design question. The present analysis of the LHX automated systems and their relation to the pilot indicates that a high level of workload will exist. The primary reason for this conclusion is that the amount of workload in highly automated systems is related directly to the extent of knowledge-based functions the pilot must perform in order to interact with the system effectively and efficiently. Although a large number of skill-based functions will be automated in the LHX, the automated systems proposed for the LHX still require some significant decision-making level of interaction with the pilot. The proposed automation will decrease workload in some respects, but significantly increase it in other respects. That is, the flexibility and expanded capabilities of the advanced sensor, weapon, communication, and countermeasure systems of the LHX will increase the workload in terms of knowledge-based functions, implying that pilot error could increase. At the least, the pilot often might be faced with situations where some necessary decisions or actions would either not be made on time or result in some unsafe compromise. On the basis of this analysis, it is recommended that the LHX be designed with at least a two-pilot cockpit.

The emphasis placed on the shift from skill-based functions to knowledge-based functions due to specific types of automation should not be construed as an argument against automating the

LHX. It is an argument for the further use of automation in ways that complement the advanced sensor and weapons-oriented automation now proposed for the LHX. The knowledge-based functions should be automated in ways that complement the currently proposed automation of the skill-based functions. This could be in the form of pilot decision aids along with some capability for high level decision-making. It also could be used to remove the pilot from certain decision loops altogether. The type of automation that would replace knowledge-based functions most often is referred to as artificial intelligence. However, the state-of-the-art in this field may not yet be sufficiently advanced for automating knowledge-based functions. It is this type of technology that is needed in the LHX in order to have a single-pilot cockpit. The following briefly outlines some artificial intelligence automation possibilities that would bring the LHX closer to single-pilot operation. These suggestions were not included as options in the TOD.

1. Automatic flight control: As already discussed, the TOD calls for the pilot to retain control of the aircraft's flight. This could produce high levels of workload depending upon the flight profile and the degree of precision necessary in flight control. Therefore it is suggested that flight control be so automated that the pilot actually need not control the aircraft in times of high workload. The automated flight control system can be interfaced with the navigation system so that the pilot only need "tell" the aircraft where to go and the actual flight then is completed automatically. The pilot would then become more of a commander than a 'flyer' of the aircraft.

Flight controls could still be included in the cockpit for those instances requiring direct pilot control.

2. Automated aircraft survivability/countermeasures: The pilot should concentrate on the parameters of the mission and how the mission can be accomplished in the type of battlefield scenario anticipated by AirLand Battle 2000 doctrine. Although survivability is essential for mission completion, it is often more of a passive nature and could be handled automatically (e.g., electronic countermeasures). The pilot need not be part of the countermeasures taken unless they require some action that might compromise mission completion. However, the psychological impact of this type of automation will have to be carefully assessed.

3. Automatic system status diagnosis and correction: As presented in the TOD, the pilot still is required to perform system diagnosis and correction for system status warnings or unusual events. These knowledge-based functions could be automated. The only time the pilot need be included in system status functions is when some corrective action not under system control must be performed. In order to reduce the pilot's knowledge-based functions, it is critical that the automatic system status monitoring have sufficient artificial intelligence to account for the pilot's real-time workload demands. Warning signals are useless if the pilot cannot properly respond due to other workload factors.

IMPLICATIONS FOR RESEARCH

The LHX is intended to provide the flexibility and capability necessary for survival and mission completion in the battlefield anticipated by the AirLand Battle 2000 doctrine. In order to accomplish these goals, not only will the engineering design requirements push the limits of technology, but a new man-machine relationship will have to be established. The pilot will be no longer the controller of a relatively 'passive' machine, but will become the manager of a sophisticated, 'intelligent' system. Accordingly, biomedical research and development should be directed toward answering the unknown questions and resolving the anticipated problems that now can be determined as relevant for the realization of such futuristic systems.

Within the mission of USAARL, which includes biomedical aspects of human factors and human performance issues, there are two primary lines of research that may be needed to address questions still unresolved for LHX and post-LHX systems.

The first line of research would concern the symbiotic relationship that will be established between the man and the machine. As outlined here, the pilot will be required to perform more knowledge-based, managerial types of functions. With increasing sophistication resulting from artificial intelligence, the operator will become more of a 'partner' with the machine. There are several specific research questions that could be addressed in support of LHX and post-LHX systems. Among them are:

1. What knowledge-based, or decisional, capabilities should be automated and what should be left up to the human? Where and when can the pilot be effectively replaced? Increasingly, it is becoming evident in present research that not only are humans limited in their decisional capabilities, but machines also are limited (even the super computers) in their computational capabilities relevant to what is required in order to compute optimal solutions to certain decisions. The parameters of the most efficient and reliable man-machine decisional relation must be established.

2. Where and when can decision aids enhance pilot capabilities and information processing? What form should these decision aids take? It may be necessary or desirable to let the pilot make certain types of decisions even though his efficiency may be extremely low. The machine may be able to help, even though the pilot will have the final word.

3. Which human cognitive limitations are most relevant in determining how well the pilot functions within highly automated workspaces? Basic research has indicated that humans are limited in memory, perception, and many other higher level cognitive functions. In what manner, if any, should these limitations be compensated for through the use of automation?

The second major line of research would concern the actual interface between the man and the machine. It is evident that even current technology to be used in the LHX will extend the pilot's effective sensory range and information input to such an extent that information overload could become a serious problem. Several specific questions should be addressed.

1. How should various sources of information be integrated in order to provide a 'true' representation of the battlefield conditions (i.e., how is situational awareness to be achieved)? How should the integrated information be displayed to maximize pilot performance?

2. Advanced sensor systems, coupled with artificial intelligence analyses, will be capable of providing a wide range of information types rather than just status information. What symbologies or formats are most effective or efficient for presenting the types of structural, factual, or procedural information available through artificial intelligence-based sensor or command, control, and communication systems? How are three- and four-dimensional world views best displayed or simulated in two-dimensional visual displays?

3. What types of 'personalized' displays, those displays generated to enhance the strengths and minimize the weaknesses of a specific pilot, can be used? Does this presentation method significantly benefit the pilot? It is self evident that people are not all the same. The level of efficiency and fighting capability desired for future systems might be achieved only by taking into account and providing appropriate compensations for limitations on an individual basis.

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Annex R-IX to Appendix R

NUCLEAR, BIOLOGICAL, AND CHEMICAL (NBC) CONTAMINATION PROTECTION, DETECTION, AND DECONTAMINATION CONCEPTS ANALYSIS FOR THE LIGHT HELICOPTER FAMILY (LHX)

R-IX-1. The report, "Nuclear, Biological, and Chemical (NBC) Contamination Protection, Detection, and Decontamination Concepts Analysis for the Light Helicopter Family (LHX)" is reproduced on the following pages. The report was prepared by Richard N. Armstrong of the Human Engineering Laboratory, Fort Rucker, AL.

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NUCLEAR, BIOLOGICAL, AND CHEMICAL (NBC) CONTAMINATION PROTECTION, DETECTION, AND DECONTAMINATION, CONCEPTS ANALYSIS FOR THE LIGHT HELICOPTER FAMILY (LHX)

Prepared by:

Richard N. Armstrong

U.S. Army Human Engineering Laboratory

15 May 1985

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NUCLEAR, BIOLOGICAL, AND CHEMICAL (NBC) CONTAMINATION PROTECTION, DETECTION, AND DECONTAMINATION CONCEPTS ANALYSIS FOR THE LIGHT HELICOPTER FAMILY (LHX)

1. INTRODUCTION.

The official public policy of the Soviet Union is one of international limitation and control of nuclear, biological, and chemical (NBC) weapons. There is evidence, however, that the official policies are ignored when the Soviets are directly or supportively involved in military conflicts.[1-6] Soviet-backed forces have reportedly used chemical weapons as a means to destroy whole villages of H'mong tribesmen in Laos. Evidence also points to the use of chemicals in Cambodia. More recently, there have been indications that Soviet occupation forces in Afghanistan are using chemical agents in an attempt to neutralize the resistance of the Afghan patriots.[5, 6] One of the widest disparities between North Atlantic Treaty Organization (NATO) armed forces and those of the Warsaw Pact nations is in chemical warfare capabilities. In chemical warfare, the greatest tactical advantage accrues to the nation with the greater capability. History has shown that when such a disparity has existed, it has generally been exploited, as in Laos and Afghanistan.

The Soviets have employed and are expected to continue to employ NBC weapons. Their vast arsenal of NBC weapons and delivery systems has considerable range and mobility. NBC weapons are relatively cost effective compared to other weapons and can be delivered by artillery, missiles, bombs, or aerial spray systems. The Soviets are well-equipped and prepared to fight an offensive conflict in an NBC environment.

Soviet doctrine emphasizes surprise attack and a massive offensive effort to rapidly penetrate the defender's main line of defense, to encircle pockets of resistance, and to thrust into the rear area. The advantages of using NBC weapons to accomplish the Soviet offensive objectives are numerous. Chemical agents, biological agents, and radiological hazards can be used to kill or incapacitate an enemy while leaving terrain, buildings, military equipment, and supplies intact. Such weapons can also be used to contaminate selected terrain, thereby creating a barrier that hinders free tactical movement and channels maneuver forces.

To enhance their capability to fight and survive in a chemical environment, the Warsaw Pact nations have fielded a wide range of NBC offensive and protective systems including personnel protective clothing and detection, identification and decontamination devices. The net result is a formidable capability to fight and survive in an NBC environment.

The future battlefield may be characterized by the extensive use of NBC weapons, particularly during the initial attack. The forward line of own troops (FLOT) will most likely be hit with nonpersistent agents while more persistent agents may be used further to the rear on secondary troop positions, counterattack approaches, reserve assembly areas, supply depots, artillery locations, and airfields.[7, 45]

Army aviation, especially the new LHX, can expect to encounter more contaminated areas than most ground units. Aviation assets will not only be located near or with ground troops but will also fly missions in or through contaminated areas. The tactical mobility of aircraft allows them to cover considerable terrain in a short period of time, enabling them to encounter and fly through several contaminated areas during a single mission. If the LHX is to be successful in future combat, it must be designed to protect the aircrew, to limit contamination of the aircraft and its weapons, and to aid in decontamination. Defensive measures must be designed into the LHX to prevent an increase in air or ground crew workload, to maintain a high level of crew and mission effectiveness, and to minimize the Army's manpower and training requirements. The purposes of this analysis are to assess the threat to Army aviation, specifically to the LHX, posed by the use of NBC weapons; to examine the effect of those weapons on crew performance; and to evaluate available techniques to reduce the impact of NBC weapons on the LHX mission effectiveness. This analysis uses the deficiencies outlined in the Army Aviation Mission Area Analysis as a baseline, supplemented with the LHX Trade-Off Determination (TOD) and other current NBC evaluations and field tests. The goals outlined in AR 70-71, Nuclear, Biological, and Chemical Contamination of Army Materiel, were also addressed.

2. HUMAN PERFORMANCE.

a. General. Degraded aircrew performance during and after an NBC attack depends on the quantity, magnitude, and type of weapons and agents, as well as the distance personnel are located from the point of employment and the level of individual protection provided. Because of the wide variety and complexity of the effects of each specific type of weapon and agent, a detailed discussion is not included in this analysis. This discussion is limited to an overview of the overall impact each type of weapon system has on human performance. In general, the effects of NBC weapons on soldiers include physical discomfort, psychological stress, nausea, burns, flashblindness, loss of consciousness, disorientation, and death. All of these factors contribute to degraded soldier performance and reduced mission success.

b. Nuclear. The use of nuclear weapons not only causes damage to vehicles, buildings, and supplies, but also degrades soldier performance and causes casualties. The effects that most impact an aircrew fall into four categories--blast, nuclear radiation, thermal radiation, and flashblindness. Each has a different effect on the human body and performance levels which will be described in subsequent paragraphs.

High-pressure blast waves that occur seconds after a detonation create environmental overpressures which can cause immediate death or injury to individuals by their crushing effect. Sudden compressions of the body result in the collapse of the thoracic and abdominal walls, as well as the membranes of the ear. These compressions can produce hemorrhage and ruptures of the lungs and eardrums. A temporary loss of consciousness has also been associated with a nuclear blast. The net result could be a fatality, a casualty that requires medical attention, or, at a minimum, a degradation in soldier performance.[10, 11]

The wind blast from a nuclear detonation also indirectly effects human performance adversely. The danger is caused by flying objects picked up by the wind and thrown randomly about the battlefield. The high-speed winds propel small objects like glass, tree limbs, or debris at great speed, turning them into potentially lethal missiles. Data obtained during nuclear weapon tests reveals that, at relatively low-peak overpressure values, small glass fragments and stones can reach velocities of 285 feet per second (fps). Large missiles, weighing approximately 10 pounds (lb), can cause concussions and skull fractures at impact velocities as low as 15 fps. The wind from a nuclear detonation can also physically throw exposed individuals several hundred feet.[11]

Thermal radiation caused by a nuclear explosion causes injuries in two ways--by direct absorption of the thermal energy (flash burns) and by fire caused in the environment. Close to the explosion, the thermal output will be so great that all objects will be incinerated. At greater distances, the burns received by personnel will range from a mild sunburn to extensive third-degree burns.[11] Individuals may rapidly become incapacitated and require medical treatment. The aircraft itself and the aircrew's clothing will afford some protection but the aircrew's exposed skin areas (like the face) will be adversely affected. Second-degree burns around the aviator's eyes can easily cause him to lose his visual capabilities. The pain of skin burns will also be detrimental to human performance.

Radiation emanating from a nuclear explosion has a somewhat different effect. The effects of radiation on humans are primarily deterioration of the body's blood cells, bone marrow, gastrointestinal systems, and the central nervous system. Unlike other nuclear effects, radiation may cause casualties without readily apparent symptoms. The radiation components harmful to humans are outlined in figure 1. At radiation levels of 650 cGY or more, the effects are lethal; individuals are incapacitated within minutes and remain functionally impaired for days, until death occurs.[12] Even at low levels of radiation, the near-term effect on the human--nausea, vomiting, headache, dizziness, and disorientation--will reduce effectiveness, particularly on a pilot attempting to fly and fight in an Army helicopter.

Radiation Component	Total Accumulated Dose (cGY)	Detrimental Effects on Humans
Gamma rays and neutrons	150	No lethal effect but may cause vomiting and nausea with a predicted 5-percent casualty rate.
	650	Lethal--bone marrow does not produce blood cells--with possible death in several weeks.
	3,000	Immediate temporary incapacitation; personnel are incapacitated within 5 minutes, remain so 30-45 minutes, and then recover but are functionally impaired until death in 4-5 days.
	8,000	Immediate permanent incapacitation; personnel are incapacitated within 5 minutes and remain so for physically demanding tasks until death in 1-2 days.
Beta particles		Skin burns on contact; hazardous if ingested. Not considered tactically significant.
Alpha particles		Hazardous if ingested; many alpha emitters mimic biologically active elements and are preferentially bound to specific organs. Not considered tactically significant.

Figure 1. Radiation components harmful to humans.[34]

Flashblindness and retinal burns are perhaps the most far-reaching effects of a nuclear explosion with temporary effects on the aircrew extending out much further than the overpressure, wind blast, and thermal radiation impact. Flashblindness is the temporary loss of vision caused by the initial brilliant flash of light produced by the nuclear detonation.

During daylight, it may take the eye up to 2 minutes to recover from flashblindness. At night, the situation is more devastating; loss of full night dark adaptation can last 30 minutes or more.[11] These recovery periods are unacceptable when flying an aircraft. Retinal damage caused by the direct and indirect viewing of the high-intensity flash is more severe than flashblindness. In retinal burns, the damage is permanent. A portion of the retina of the aviator's eyes can be impaired, creating a blind spot in the visual field of both eyes.

A 1-megaton, multiburst yield nuclear attack, spread randomly over a division area, has been estimated to destroy 7 percent of the rotary wing aircraft by blast while 83 percent of the unprotected airborne pilots will experience a level of flashblindness that could result in a crash.[13] With a 50-kiloton yield at 1,000 feet above the ground, aviators will be blinded for 5 seconds or more during the day, within a 14.3-nautical mile (nm) range of the burst and as far away as 32.5 nm at night.[13, 14] During nap-of-the-earth (NOE) flight, flashblindness for a number of seconds could be disastrous. The overall effect of flashblindness will certainly have an adverse effect on human performance.

c. Chemical. The overall effect that chemical exposures will have on human performance is dependent on the extent and type of the chemical used, the exposure time, the breathing rate, and the measures taken to protect the soldier.

The major chemical threats that the aircrew can expect to encounter during combat including blood, nerve, choking, and blistering agents in the form of gases, aerosols, and liquids, are depicted in figure 2. The effects of chemicals on aircrews vary from mild irritation to incapacitation and death. For example, if the crewmember is exposed to nerve agents when wearing normal flight clothing, the physiological impact varies from nausea and vomiting to unconsciousness and eventually death. The casualty rate under those conditions would completely destroy combat effectiveness. Even when the chemical attack results in a lesser degree of degradation, the aircrew may be unable to fly the aircraft and to perform their mission. They may very well end up under medical care for days or months. A major concern for the aviator in the NBC environment is miosis. Extremely small concentrations of chemical agents, especially nerve agents,[4] reaching the eye can induce pain and cause the individual's pupil to constrict, thereby causing diminished vision. A reduction in visual capability can have a catastrophic impact within seconds.

Type of Agent	Disseminated As	Effects on Man	Rate of Action	Protection	U.S. Agent Equivalents	
					Symbol/Name	Characteristics
Nerve	Aerosol, vapor, or liquid	Vomiting, cramps, seizures, coma, asphyxia, or death.	Rapid (inhaled); slow (skin absorption)	Mask and clothing	GA/Tabun GB/Sarin GD/Soman VX Thickened G-agents	Colorless, odorless
Blister	Liquid or vapor	Blisters skin, destructive to respiratory system, can cause temporary or permanent blindness and death.	Slow to form blisters; rapidly affects eyes	Mask and clothing	HD/mustard HN/nitrogen mustard Lewisite	Yellow droplets Dark droplets Dark, oily droplets odor of garlic
Blood	Vapor	Eye irritation, lung irritation, death.	Rapid	Mask	AC/hydrogen cyanide CK/cyanogen chloride	Colorless, odor of bitter almonds
Choking	Vapor	Kills by flooding lungs with body fluids.	Rapid to delayed	Mask	CG/phosgene	Colorless, odor of newly mown hay

Figure 2. Chemical agent characteristics.[8, 9, 49]

d. Biological. Biological agents consist of living microorganisms much like those that create normal illness in humans and animals. Toxins are the by-products of living microorganisms that react similarly to chemical agents in the human body. Figure 3 reflects some of the typical biological agents that may be used in war. Most biological agents differ from chemical agents in their reaction time. Chemical agents and toxins tend to have an adverse effect on the individual in a few minutes; with biological agents, other than toxins, there is a considerable delay (hours to days) from the time the individual is exposed to the agent until symptoms appear. Due to that time delay, biological agents are expected to be used over a widespread area, possibly before a major conflict. Their application, in a tactical sense, is expected to be very limited. Although Army aviation, as a member of the combined arms team, must be concerned with biological agents, the impact on the system design of the LHX is not expected to differ much from that applied to chemical defense.

Main Group	Subgroup
Bacteria	Anthrax, plague, brucellosis, typhoid, dysentry
Rickettsias	Queensland fever, Rocky Mountain spotted fever, other types of spotted fever
Viruses	Yellow fever, smallpox, encephalitis
Fungi	Coccidiomycosis, blastomycosis
Toxins	Botulism, staphylococcus, mycotoxins

Figure 3. Bacteriological and biological agents.[8, 9]

3. NBC DEFENSE.

a. Approaches. Some type of defense is needed if aviation personnel are to fight and to perform effectively in a contaminated environment. Four approaches--avoidance, collective protection, medical measures, and individual protection (figure 4)--are currently envisioned to provide soldiers protection from the adverse effects of NBC weapons. All four approaches have merit, but each has inherent limitations and none alone provides the ultimate answer.

Avoidance: Avoid the contaminated area.

Medical Measures: Administer immunizations and pretreatments to individuals prior to an attack and antidotes after the attack to counter the agents' effects.

Individual Protection: Provide individual protective suits to allow operation in the contaminated environment.

Collective Protection: Remain in protective shelters or sealed vehicles that prevent contamination from reaching individuals.

Figure 4. NBC defense approaches.

b. Contamination Avoidance.

The most effective means to prevent casualties and the debilitation of aviation personnel during an NBC attack is to avoid the threat completely. In some cases, aircraft may be able to fly around contaminated areas and still accomplish their mission.

The option of avoidance will, however, only be successful if aviation units and aircraft are warned in time to avoid the threatening agent. The location of contaminated areas must be accurately identified before the aircraft enters these areas. Standoff contamination detection devices, discussed in detail later in this report, are required for the LHX to use the option of contamination avoidance.

Contamination avoidance is a valuable tactical option that can increase combat effectiveness during some battles, but not all. Other NBC defensive measures need to be employed to protect the LHX aircrew during periods when they must fly into contaminated areas.

c. Medical Measures.

To overcome the adverse effects that NBC weapons have on human performance, pretreatments or antidotes can be used before and after exposure to agents.

Biological warfare casualties can be reduced if soldiers are immunized prior to attack. Agents used in biological warfare spread diseases like those that are found in various parts of the world today--typhoid, influenza, and anthrax, to name a few. Some of the effects of biological agents can be countered by promoting good hygiene among the troops, but immunization seems to be more effective. Because of the wide variety of diseases, the biological agent most likely to be used must be known so that personnel can be provided the proper immunization. The field commander must rely heavily on intelligence sources and monitor local water and food supplies for that information.

Protection or immunization against chemical agents is not quite as effective as for biological agents. Pyridostigmine, available in pill form, if taken a short time before nerve agent exposure, will reduce the probability of death and will protect the soldier's health but will do little to maintain his maximum combat effectiveness.[16] Atropine and pralidoxime, the more widely available self-administered antidotes for chemical agents, will save the lives of individuals who have received lethal doses of a nerve agent and will reduce the severity of sublethal doses if administered immediately after exposure. However, side effects like nausea, vomiting, disorientation, loss of visual accommodation, and pain could result in degraded performance.

A second and possibly more serious problem arises when the individual inadvertently administers excessive atropine or other antidote when not actually subjected to a nerve agent. Premature multiple injections may cause the individual to become incapacitated by the antidote itself.

A review of the effects that such therapeutic compounds have on man[16, 17] indicates possible performance decrements which include increased heart rates, reduced visual accommodation, dizziness, sleepiness, fatigue, and reduced cognitive capability for multiple doses.

Generally, when considering the medical evidence concerning chemical and biological agent prophylactic and antidote measures currently available to Army aviation, one can conclude that the use of medical measures as an NBC defense will save lives, reduce casualties, and may boost the morale of the troops. On the other hand, the decrement in human performance is still significantly high and reduces mission effectiveness. Research efforts are currently ongoing to improve pretreatments and antidotes, but, at this time, they do not appear to be a viable alternative to collective or individual NBC protection in the LHX.

d. Individual Protection.

(1) Current systems.

Individual protective clothing has received considerable attention as a means to provide the required chemical protection for aviation personnel. The major argument for emphasizing this type of protection within the Army is that soldiers cannot always fight from a collective area or vehicle and therefore need individual protection. This philosophy has been carried over to Army aviation on a similar premise--that the likelihood of keeping chemicals outside the aircraft crew station is very difficult. For example, an aircraft returning from a mission may have to land in a contaminated area and the pilot may have to leave the aircraft. In doing so, the inside of the cockpit could become contaminated. The same would be true of utility aircraft picking up troops from a contaminated area. Our current aircraft are not designed to prevent agents from entering the cockpit, so they could easily be contaminated in a matter of seconds when flying through a vapor cloud or toxic rain or when just sitting on the ground. The protective clothing approach does, however, introduce many and severe handicaps on the human operator resulting in degraded human performance.

The aviator's current NBC protective clothing (figure 5) consists of a standard flight suit, a chemical protective overgarment, a protective mask, the standard SPH-4 helmet with chemical hood, a set of protective overboots, and a set of chemical agent-resistant gloves. This version of protective gear has been in the inventory for more than 10 years. Depending upon the anticipated threat, the mission-oriented protective posture (MOPP) may be varied to provide flexibility in mission accomplishment. The various MOPP levels of protection and associated protective clothing worn are summarized in figure 6. MOPP selection for a given time period is based on the threat, the mission, vulnerability, and weather. The theater commander hopefully orders MOPP 1 before the use of chemical agents while MOPP 4 is used if an attack occurs or is imminent.[18] Aviation personnel must fly in MOPP 4 whenever the ground forces are in MOPP 1. The reason for this policy is the difficulty in, and sometimes impossibility of, aviators donning protective gear in time to prevent impairment or death while flying an aircraft. Aviators may have little time to don protective equipment before they are disabled by agents. The period in which aviation personnel are expected to be in MOPP and to continuously wear the NBC protective ensemble may be from 2 to 12 hours. If properly fitted, the current chemical protective clothing does provide a life-saving function and allows aviation missions to be accomplished at some degree of effectiveness; however, numerous problems have been reported that severely degrade human performance. The reported problems with the current NBC ensemble have highlighted heat stress, but they also include restricted movement of the torso, head, legs, and arms; a lack of manual dexterity; a restricted field of view; optical distortions in the mask lens; the inability to eat or drink; the need to partially remove the clothing to defecate; the incompatibilities with aircraft and other life-support equipment; and difficulty in safely removing contaminated clothing. Each of these is treated in more detail in the following paragraphs.

Figure 5. Aviator NBC protective clothing.

MOPP	Overgarment	Overboots	Mask/Hood	Gloves
0	Carried	Carried	Carried	Carried
1	Worn open or closed based on temperature	Carried	Carried	Carried
2	Worn open or closed based on temperature	Worn	Carried	Carried
3	Worn open or closed based on temperature	Worn	Worn with hood open or closed based on temperature	Carried
4	Worn closed	Worn	Worn with hood closed	Worn
Mask Option	Carried	Carried	Mask worn	Carried

Figure 6. MOPP levels.

One of the major limitations imposed by protective clothing is related to heat stress.[19-25] The current chemical threat dictates that the protective clothing be designed and constructed so that it will prevent chemical agents from penetrating through the garment. In doing so, an effective barrier is also established which reduces the ability of the human body to dissipate heat by means of evaporation and convection. The net effect is the retention of body heat, with escalating effects such as fatigue, weakness, and ultimately physiological collapse of the human. Even when heat stress is below the physiological collapse level, it can cause human performance decrements in tasks that require mental performance, manual dexterity, visual attention, tracking ability, vigilance, and psychomotor performance.

The magnitude of the reduced human performance due to heat stress is dependent on the individual's physical condition, the level of activity or workload, and the amount of time that the level of activity is maintained. In general, the aviator's workload while flying an aircraft is less strenuous than that of ground troops or aviation maintenance personnel, but missions of long duration without rest in a cool or sheltered area will have a major impact on crew performance. This will be especially true in the event of surge operations where the threat may dictate maximum employment of aviation assets for a 72-hour period. Figure 7 provides an overview of what can be expected of physically fit young soldiers wearing chemical protective clothing.[25] The predicted percentages of heat casualties shown are based on the point at which the body's core temperature reaches a value where the human is physically incapacitated to a degree that the mission cannot be completed.

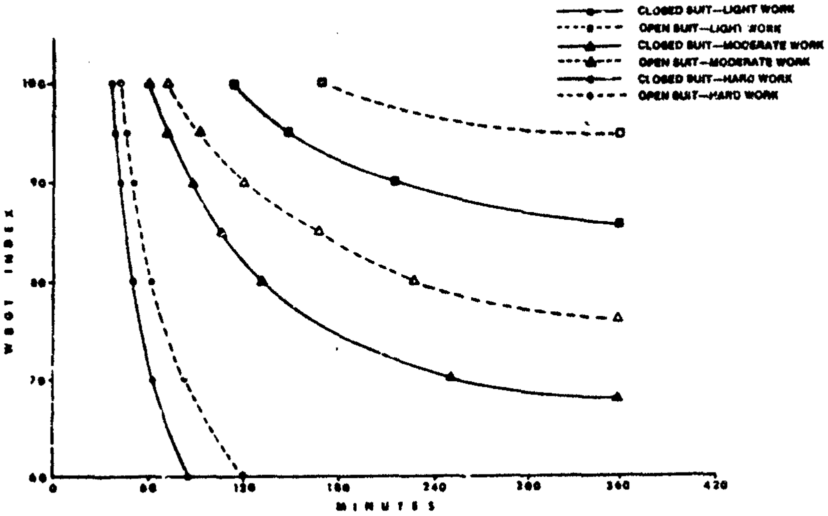

Figure 7. Predicted time to 50-percent unit heat casualties.

Aviators flying in NBC protective clothing (MOPP 4), without auxiliary cooling in a closed canopy aircraft, can be equated to the closed suit, moderate work rate. When considered in the context of a typical flight mission conducted in a hot climate (above 85°F WBGT), performance decrements within 2 hours may be such that the aviator will require a long rest in a cool environment to recuperate after each flight.[20, 24]

Flight evaluations, conducted in current helicopters found that aviators in standard MOPP 4 gear are less mission-effective when heat stressed.[20, 24] Based on these studies most acclimatized aviators, while wearing standard NBC flight gear, and flying in extremely hot and dry environments, can complete one or two consecutive missions without suffering from heat stress providing they drink adequate amounts of water.

New fabrics are under development for use in NBC garments that are expected to provide some relief from heat stress but not completely solve the heat stress problem. The design of the LHX must address the NBC heat stress problem if that aircraft is to be effective on the battlefield.

In addition to the heat stress problem caused by individual NBC protective clothing, there is the problem of incompatibility with crewstation visual requirements, flight controls, avionics systems, and crewstation controls and displays. The aviator NBC mask, for example, restricts the aviator's field of view. When wearing the NBC mask, pilots have reported spatial disorientation, depth perception problems, and reduced visual acuity. In addition, the current NBC masks and aircraft target acquisition displays and sighting systems are not fully compatible. The structure of the lens of the NBC mask prevents the aviator from placing his eyes as close to the targeting optics as he can under normal conditions. As a result, the field of view of the target area is reduced and full use of the weapon system is impaired.

The NBC overgarments, boots, and gloves also degrade aviator performance. When aviators don their standard flight gear and NBC protective clothing, they are restricted from easily reaching some of the aircraft equipment switches and controls.[22, 26-28] The butyl rubber gloves, for example, introduce manual dexterity and tactile sensitivity problems.[28, 32] The gloves are bulky, especially when worn with Nomex flight gloves, and retard the aviator's ability to feel the aircraft controls and system switches, thus requiring the aviator to shift his gaze inside the aircraft to find the appropriate switch before activating it. While this is undesirable in any aircraft, it becomes extremely critical in a single-crew LHX.

Taking into consideration all the problems discussed above, the current individual NBC protective clothing does provide a limited capability to perform Army aviation missions in an NBC environment. The shortcomings associated with that approach (heat stress, aircraft incompatibility, restricted vision, increased stress and fatigue, and reduced crew performance) all contribute to a degraded mission capability that prevents the full effective use of helicopters. This is true any time the aircrew is forced to fly in full protective gear, even when not exposed to actual chemical agents. Those shortfalls need to be alleviated if maximum use of the potential capabilities of the LHX are to provide the increased capability required to meet the threat during future combat.

(2) Protective clothing improvements.

(a) Cooling.

Heat stress is the major shortcoming associated with the current aircrew NBC protective clothing systems. The options available to alleviate that shortcoming are to provide a sealed crew station that does not require protective clothing to be worn, to modify the clothing to allow the aviator's body heat to be dissipated, or to provide some type of auxiliary cooling. Modifications to the NBC protective clothing system are under development but they are not expected to provide significant improvement in heat stress reduction. To protect the individual from the threat, the clothing must be designed to prevent chemical agents from penetrating the garment. This chemical agent barrier, in turn, decreases the rate at which the individual's body heat is dissipated through evaporation and convection.

One approach to providing auxiliary cooling that would reduce the heat stress problem in aircraft would be to cool the entire cockpit to a temperature level below the 75-degree Fahrenheit (°F) wet bulb globe temperature (WBGT) established by the aircrew standardization committee. The disadvantage of this option is the space and weight of a unit that would sufficiently cool the crew station. Based on the data provided in the LHX TOD study, the weight would be about 156 pounds.

Another solution to the NBC heat stress problem, which appears to have considerable potential, is microclimate conditioning systems. A number of such microclimate conditioning systems, which operate on the same basic principle, are under development (figure 8). A thin, undergarment-like body covering, interlaced with a series of hollow channels or tubes, is worn underneath the normal flight clothing or fatigues. Precooled fluid or air is then passed through these hollow channels to provide a medium for heat to be transferred from the body to the cooling medium.

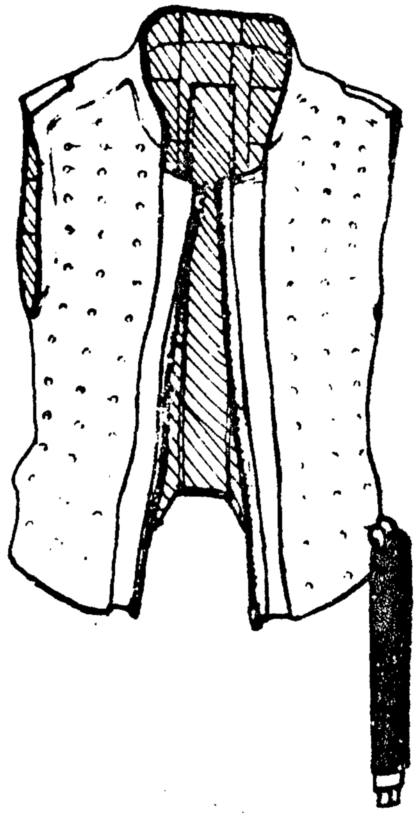

Figure 8. Microclimate cooling vest.

During laboratory tests[37, 38] of different liquid-cooled undergarments, it was reported that maximum cooling could be obtained when the undergarment covered the torso, head, arms, and legs. However, during recent flight tests, a vest-type undergarment that provided torso and some head coverage was sufficient for flight missions. Adequate cooling can be provided for unlimited time durations. The disadvantage is that these systems are, for the most part, restricted to use inside or in close proximity to a vehicle or other fixed facility. An electrical power source is needed to maintain the liquid or the air at the proper temperature levels. In addition, when disconnected, the vest adds an additional layer of clothing that could contribute to heat stress.

Field and laboratory tests have been conducted in which men in MOPP 4 wore a liquid- or air-cooled vest during simulated missions in an M-1 tank.[37, 40, 41] The results of those tests confirm the potential of undergarment cooling systems for vehicular use. During the M-1 test, individuals were able to complete the 3 1/2-hour mission without heat stress problems, even when the internal vehicle temperature reached 90°F WBGT. When in MOPP 4 and wearing the cooling vest, the tank crew was reported to be able to maintain a high level of mission effectiveness with little or no increase in body core temperature. In comparison, similar data collected with the individuals in MOPP 4 without the cooling vest revealed that body core temperatures rose rapidly, mission errors were detected within 30 minutes of the mission start, and mission tolerance was limited to less than 2 hours.

During the UH-1H flight test discussed previously, 13 aviators wearing standard MOPP 4 garb and a liquid-cooled vest were able to complete approximately 4 hours of the assigned mission with no sign of physiological decrement due to heat stress.

The estimated cost, weight, and power for a two-aircrew microclimate cooling system defined in the Trade-Off Determination study conducted by the U.S. Army Aviation Systems Command (AVSCOM) are as follows:

-- Weight = 92.5 lb

-- Power = 7 shaft horsepower (shp)

-- Cost = $35,000.00

Additional efforts are in process to further reduce the weight to less than 50 lb and a cost near $5,000. Microclimate cooling systems appear to be one of the better options to provide cooling to the LHX aircrew when flying fully clothed in NBC protective gear. The system could also provide crew cooling capabilities and increased mission effectiveness when operating in normal combat gear (flight suit, armor vest, and survival vest) in high-temperature environments.

(b) NBC clothing restrictions.

The other major shortfalls of NBC protective gear included restricted movement, reduced manual dexterity, restricted field of view, inability to eat or drink, and incompatibilities with the aircraft and other life-support equipment.

Lightweight NBC flight suits under development, if successful, should allow the aviator a little more freedom of movement. Lightweight gloves could potentially provide better manual dexterity and tactile sensitivity than the gloves currently used. The aircrew integrated helmet (figure 9), which is under development, is also expected to overcome some of the limitations of NBC protective gear. The goal is to integrate into one helmet protection for the aviator from chemical agents, flashblindness, lasers, and acoustical noise, and head impact protection.

Figure 9. Aircrew integrated helmet.

These new protective systems will do much to alleviate some of the shortfalls in current NBC equipment, but they will not eliminate enough of the problems. The LHX design concept, for example, is expected to use a helmet-mounted display system to provide the aviator with flight and target acquisition information without him looking inside the crew station. The electronic hardware required to be mounted on the aviator's helmet is not necessarily compatible with the integrated helmet now under development. The design of the LHX can have a considerable impact on reducing the current NBC protective equipment limitations. Adequate space needs to be provided in the LHX to allow the aviator freedom of movement when wearing not only NBC gear, but ballistic armor protection, a survival vest, and cold weather clothing. The manual dexterity limitations imposed by NBC gloves can be reduced by proper design and placement of the LHX controls, switches, and displays. Attention must also be paid to the LHX sighting system and display design to assure they are compatible with the lens of the NBC protective mask.

One method to alleviate all the shortfalls discussed above would be to provide the aircrew full collective protection.

e. Collective Protection.

The fourth approach to providing NBC protection to the crew of the LHX involves the use of collective protection. A collective protection area is one that shields the individual from the outside contaminated environment by means of a structure or cover (tent, building, or aircraft cockpit) that is sealed and maintains a positive pressure to prevent toxic agents from entering. The internal environment is further enhanced by the use of filters that remove contaminants from the air and environmental conditioning units that maintain the air at the proper temperature. The advantages of such collective protection are numerous. They allow individuals to operate at maximum efficiency by providing a "shirt-sleeve" environment. If the LHX were designed to provide full collective protection (filter, air heating and cooling, and crew station positive pressure) during flight, human performance and the probability of mission success in the NBC environment could be significantly increased. The aircrew would no longer be hampered by the heat stress, restricted vision, reduced mobility, and manual dexterity problems encountered in current protective NBC gear.

Another major advantage to collective protection would be the protection of the LHX aircrew during an initial attack. As mentioned earlier, when the theater commander orders the ground troops into MOPP 1, the aircrew will fly in full MOPP 4. The commander's decision to wear NBC protective gear will often be based on intelligence reports that indicate the use of NBC weapons is expected. If the intelligence information is not timely, aircrews in flight could be caught unprotected. For example, if the use of NBC weapons were to occur without prewarning today, aircrews flying without NBC protective gear could become NBC casualties. The net result may very well be the loss of all exposed aircraft and crews. Such a loss of valuable aviation assets at the beginning of a conflict would put the U.S. forces at a severe disadvantage.

Considering that the Warsaw Pact forces outnumber NATO forces, Army aviation cannot afford to be placed in such a position. If aircraft were provided full collective protection, that problem would be avoided.

The collective protection approach to NBC defense not only provides aircrew protection, but provides protection to the crewstation equipment, avionics, controls, and display systems. Collective protection for the crewstation would reduce the need to decontaminate the interior of the aircraft by eliminating the exposure of the crew compartment to chemical agents.

The collective protection approach, like all other NBC protective measures, is not without disadvantages; the main disadvantages are the penalties associated with space, weight, power, and cost. Applying innovative engineering design should, however, reduce these penalties.

A second disadvantage of collective protection is the probability that the aircraft interior could still become contaminated. This could occur if enemy gunfire penetrates the aircraft, when the aircrew enters or leaves the aircraft while in a contaminated area, or when the landing sites are hit with chemical agents while the aircraft doors are open.

f. <u>LHX NBC Defense Approach Summary</u>.

Army aviation can expect to encounter a formidable NBC threat in future conflicts. The Soviet Union and the Soviet-backed forces have the capability to employ a vast array of NBC weapons and the capability to protect their own troops during such an attack. The LHX must incorporate design features that can successfully counter that threat. The four NBC defense approaches to protect the aircrew from the NBC threat and to maintain a high level of effectiveness on the battlefield include contamination avoidance, medical measures, individual protection, and collective protection. The LHX combat and materiel development community must determine how to optimally use each NBC defense approach while minimizing the shortcomings of each approach.

Contamination avoidance is a tactical measure that can be advantageously used when time and the combat situation permit. To enhance that advantage, the LHX design needs to incorporate detection devices that will provide the aircrew with information concerning NBC contamination in their immediate area and at some distance away from the aircraft. Contamination, however, cannot always be avoided. There are times when the battle conditions will require the LHX to enter contaminated areas.

Medical measures that use pretreatments and antidotes to counter the chemical threat can save lives and reduce casualties, but the degradation in human performance is still significant and will reduce mission effectiveness on the battlefield. The LHX must therefore rely on other measures to protect its crewmembers.

The remaining two options that provided the best overall potential for the LHX NBC defense are collective and individual protection.

Collective protection, with an LHX that is fully sealed and pressurized to prevent contaminated agents from entering the aircraft, would provide a considerable tactical advantage. Full collective protection would allow personnel to operate in normal combat clothing, thereby overcoming the performance decrements imposed by protective clothing. In addition, collective protection would also protect the avionics and other systems inside the aircraft from destructive agents and the caustic solutions required for decontamination.

The collective protection system, however, cannot assure total survival on the battlefield if enemy fire destroys the integrity of the sealed aircraft, if an emergency landing is made in a contaminated area, or if the aircrew or passengers enter or exit the aircraft in a contaminated area.

Current protective clothing that encapsulates the individual in an NBC protective suit and mask provides a life-saving capability while allowing the individual to continue to operate on the battlefield, but at reduced effectiveness. A considerably reduced level of effectiveness will not be acceptable on the battlefield of the future.

The most viable solution for the LHX appears to be a hybrid system that provides both collective protection and individual protection. Such a system would allow the aircrew to operate in a pressurized aircraft, partially or fully clothed in NBC gear.

When the integrity of the collective protection system is maintained and the crewstation is contamination free, the aircrew could operate in partial NBC gear. When approaching a known contaminated area or when the aircraft detectors indicate the aircraft is in a contaminated area, the mask and gloves could be donned to provide full protection. This approach would allow maximum effectiveness to be obtained when not in a contaminated area as well as assured protection to the aircrew when in a contaminated area.

For this concept to work, NBC agent detectors must be located to detect agents both inside and outside the aircraft. The aircrew would then be able to tell when they are in a contaminated area and whether the contamination has penetrated the crewstation. Standoff remote detection that would warn the aircrew before a contaminated area is entered would be best.

A cooling system must also be incorporated into the crew station to provide adequate cooling for the aircrew while in full NBC protective gear. The type of cooling used (environmental cooling system or microclimate cooling vest) would depend on the technology to produce adequate cooling at the least cost, weight, and power penalty. The AVSCOM LHX TOD study indicates that a hybrid system best fits that need. The cooling capacity should meet the requirements for the comfort zone defined in Military Standard (MIL-STD) 1472.

In addition, the LHX crewstation design must incorporate features that alleviate the other restrictions and workload-producing problems associated with NBC protective clothing, like limited visual capabilities, reduced freedom of movement, and manual dexterity and tactile sensitivity degradation.

The crewstation configuration and the design of the controls and displays should provide adequate room and spacing for the aviators to operate the LHX when attired in NBC clothing and other life-support equipment.

4. DETECTION.

a. General.

The success of the contamination avoidance and the use of protective equipment as viable options for NBC defense are based on the assumption that aviation personnel can identify the location of contaminated areas quickly. Contamination cannot be avoided if its location is not known. The effectiveness of NBC protective gear is dependent on the soldier being warned early enough to don his NBC gear before exposure to agents.

To determine if an NBC attack is about to occur or has occurred and to identify areas that have already been contaminated, detection equipment must be provided that allows for the detection of agents or contamination, preferably at a distance well ahead of the aircraft or ground units. Also, the aircrew will need the NBC intelligence provided by other systems. The need for detecting an NBC environment cannot be over-emphasized. It is the backbone of any NBC protection system. If the commander knows when an attack has occurred and how long the area in which his troops are operating will be contaminated. he can more effectively conduct the battle.

The ideal NBC detection system would be one that possesses the general capabilities to allow the user to accomplish the task shown in figure 10. One of the LHX mission assignments is NBC reconnaissance. Contamination detection is therefore important to the LHX from the standpoint of self-protection, primary mission effectiveness, and support of other elements of the combined arms team.

- Using standoff detectors to remotely monitor the presence, type, and levels of contamination in a specific area.
- Detect and identify all possible NBC threat agents or radiation components.
- Determine, quantitatively, the density or dose rate of the contaminant and the level accumulated over time.
- Detect and measure agent concentrations at the lowest level that degrades human performance.

Figure 10. Ideal NBC detector qualities.

b. Chemical Agent Detection.

When considering the current chemical agent detection systems, there are four classes of chemical agents that are considered a threat to aviation units in the field--nerve, blister, blood, and choking. Each has a unique effect on humans, depending on the type and levels of concentration (figure 2). The current chemical agent detection devices now available to counter the threat are shown in figure 11.

A review of the capabilities of current chemical agent detectors indicates that they do not fully meet the needs of Army aviation. There are currently no chemical detection systems designed specifically for aircraft. Current devices are all point detection types and do not provide standoff detection of agents; each must be in direct contact with the agent before it works.

Early chemical agent detection, which is important to ground units, is even more important for aviators in flight. Ground units can place point alarm devices upwind and thereby receive an advanced warning when chemical agent clouds are moving toward them. Aircraft in flight have no such advanced warning. Aviation personnel in flight must take the precautionary measure of flying in NBC protective clothing when the potential for chemical attack exists. If this is done, mission effectiveness will be adversely affected as discussed earlier. The aviator's choices are somewhat limited: (1) provide maximum NBC protection at the expense of overall mission effectiveness or (2) take the chance that NBC weapons will not be used during a given mission and fly without protective clothing. A system that provides advanced warning of the chemical threat would do much to reduce this dilemma and to improve aircrew effectiveness.

Devices	Operational Use	Minimum Concentration Measured	Limitations
M-8 paper	Chemical detector paper changes color with agent contact.	Liquid droplets bordering on the visual range.	o Point detector. o Only detects liquids. o Decontamination solutions produce false alarm.
M18A2	Detects nerve, blood, and blister agents.	Extremely low vapor concentrations.	o Point detector. o Requires trained operator. o Slow response time.
M43 chemical agent automatic alarm	Battery-operated unit continuously monitors air pulled through it and provides an automatic alarm for concentrations of nerve, blood, and choking agents.	Liquid and vapor. 0.1 to 1.0 mg/m^3.	o Point detector. o Wet chemical system. o Twelve-hour servicing period. o Response time slow. o Blister agent not detectable.
M13	Bags with dye that change color upon agent contact. Detects nerve and blister agents.	Not applicable.	o Point detector. o Only detects nerve and blister agents.
M256	Lightweight, portable unit detects nerve, blister, and blood agents.	Gas/vapor aerosols .03 to 9.0 mg/m^2.	o Does not detect choking agents. o Requires 10-15 minutes of exposure and test time.
M9 liquid agent detector paper	Chemical detector paper detects nerve and blister agents.	Liquid droplets of 100-micron size.	o False response if exposed to lubricants, gasoline, and decontaminants. o Point detector. o Liquid only. o Does not detect choking or blood agents.

Figure 11. Current chemical agent detectors.[47, 48]

Another problem with chemical agent detectors involves the type of agents detected. Nerve agents can be detected by all of the devices in figure 11. Blister agents can be detected by the M256, M18A2, M9, and M13 devices and the M8 paper. Blood agents can be detected by using the M256, the M18A2, and the M43. Choking agents can be detected only by using the M43 system. Thus, the problem is one of logistics, having the best detector at the right place at the right time. An integrated detector that could be used to measure all chemical agent groups would certainly be beneficial.

A number of developmental programs have been initiated to overcome the deficiencies of chemical agent detectors. Some of these are shown in figure 12. As shown in this figure, the chemical agent detectors now in development appear to be an improvement over those currently in the field, but they still fall short of meeting the requirements for the LHX. Most are point detectors that require placement in the contaminated area. Each is limited to detecting one or a few agents but does not detect all threat agents. The XM21 remote sensing chemical agent alarm, which is expected to be fielded in 1989, should provide some remote detection capability from a stationary position. Planned improvements of the XM21 are expected to make it a viable option for the LHX. In addition, the concept of a ground detector that would detect agents on the aircraft skin as it approaches a FARP or landing area is being investigated. Chemical and biological sensors using mass spectrometry for point sampling and active infrared (IR), laser, microsensor technology for remote detection are envisioned for the 1990s, but they are still in the early laboratory and concept study phases.

Chemical detection devices available in the inventory and those under development do not provide all the detection necessary for future aircraft. They do, however, provide some detection capability that would enhance the LHX on the battlefield. The LHX design should therefore minimally include point detection capabilities both inside and outside the aircraft, and provisions should be made to incorporate remote detection systems when they are available.

Device	Operational Use	Limitations
M256E Chemical Agent Detector	Portable kit to detect gas, vapor, and aerosols of nerve, blister, and blood agents at lower levels than the M256E.	o Point detector. o Long response time. o Does not detect choking agents.
M43A1 Detector	Battery-operated; continuously monitors vapor and aerosol nerve agents. Has automatic alarm.	o Point detector. o Does not detect blister, blood, or choking agents. o Does not identify agent type.
XM22 Automatic Chemical Agent Detector Alarm (ACADA)	Man-portable; automatic alarm detects nerve and blister agents.	o Point detector. o Does not detect blood or choking agents.
XM85/XM86 Automatic Liquid Agent Detector (ALAD)	Detects droplets of nerve and blister agents.	o Not quantitative. o Only measures liquid contaminants. o Does not detect blood or choking agents.
Chemical Agent Monitor (CAM)	Hand-held, man-operated microprocessor system that monitors people and equipment. Detects nerve and blister agents.	o Point detector. o Long time period. o Does not detect choking or blood agents.
Multipurpose Integrated Chemical Agent Detector (MICAD)	Used in vehicles and aircraft with collective protection systems.	o Point detector.
XM21 Remote Sensing Chemical Agent Alarm (SCI-REACH I)	Detects nerve agent clouds up to 3 miles by IR detection techniques.	o Must remain stationary. o Limited to nerve agents.
USAF A/230-3 System	Automatic alarm for nerve agents in vapor form.	o Nerve agent only. o Point detector. o Vapor only.

Figure 12. Potential future chemical agent detectors.[8, 46]

c. Nuclear Detection.

The current nuclear radiation detection systems suffer from some of the same deficiencies as the chemical detection systems. There are four basic components that have a detrimental effect on humans. Those components, along with the dosage levels that are presently considered detrimental to humans, are listed in figure 1. The current radiation detection devices available to detect radiation and their overall capabilities are shown in figure 13. A review of figures 1 and 13 clearly points out the deficiencies in current detection devices.

Device	Operational Use	Minimum Concentration Measured	Limitations
AN/PDR-27 Radiac Set (Geiger Counter)	Portable ground use unit. Measures dosage rate of gamma radiation. Monitors contamination of personnel, food, and equipment.	0-500 milli cGY for gamma. Detects beta.	o Does not measure neutrons. o Point detector. o Requires individual to be at contaminated source.
IM-174A/PD	Portable electronic aerial and ground monitoring and survey unit. Measures dosage rate of gamma radiation.	0-500 cGY.	o Does not measure neutrons. o Point detector. o Required individual to be in/near contaminated area. o Data reliability reduced at ground speeds above 53 knots or higher than 150 meters above the ground. Requires that an air-to-ground adjustment correlation factor be established.
IM-93/UD	Pocket dosimeter. Measures total accumulated dosage of individual gamma radiation (fallout).	0-600 cGY.	o Does not measure initial gamma or neutron radiation. o Point detector for personal use only.

Figure 13. Tactical nuclear radiation detection system.[35]

(1) None of the current devices are capable of measuring neutron radiation. Neutron radiation is considered to be a very important factor on the battlefield, particularly if enhanced radiation weapons are deployed.

(2) All three radiation detectors are point-type detection devices. These detectors must be physically located within the contaminated area and, for the most part, will require manual operation. Thus, the human operator will be exposed to the adverse effects of nuclear radiation while conducting contamination surveys. The disadvantages of this technique are obvious.

(3) The current detection devices are also deficient when attempting to detect and plot nuclear fallout so that warning can be provided to friendly forces in its path. Some type of automatic, standoff, radiation detection device is required that would allow units to monitor nuclear radiation levels without entering the contaminated area.

Hopefully, new equipment will ease some of the current problems (figure 14). The AN/ADR-6 Aerial Radiac System under development is expected to have the capability to automatically record gamma radiation levels while in flight. This will be far superior to the current method that requires an individual to be placed on the ground to measure radiation levels. This system will partially solve the problem of automatically gathering data, but the device is still a point detector that requires the aircraft to fly into the contaminated area.

Device	Range	Operational Use	Limitations
AN/ADR-6	1-1,000 cGY/hr ground dose rate.	Used in aircraft for aerial surveys.	o Point detector. o No horizontal standoff capability. Gamma only.
AN/VDR-2 Tactical, Vehicular Radiac	0.1 milli to 1,000, cGY/hr.	Replaces AN/PDR-27 and IM-174A/PD.	o Point detector. o No standoff capability.
Integrated Optical Nuclear Detonation Detection System (IONDS)	NA	Provides standoff capability for location, yield, and fallout prediction.	o Does not measure radiation levels.
IM-185 Dosimeter	0-600 cGY.	Pocket-type dosimeter. Measures individual accumulation of gamma and neutron radiation.	o Point detector. o Limited distribution.
DT-236 Individual Dosimeter	0-1,000 cGY.	Provides cumulative dose of gamma and neutron radiation.	o Requires a dedicated mechanical reader.
Pocket Radiac	1 milli cGY/hr, to 1,000 cGY/hr, 600 cGY total dose.	Pocket dosimeter/ survey and monitor.	o Point detector.
Advanced Airborne Radiac System (AARS)	0 to 1,000 cGY/hr.	Used in aircraft and RPVs for aerial surveys, automatic data (link to ground).	o Point detector. o Limited distribution.

Figure 14. Potential future nuclear radiation detection devices.

The tactical and vehicular radiac device (AN/VDR-2) which is now in the developmental phase may be of help when fielded. That system hopefully will improve present capabilities and will provide a means to measure low levels of gamma and beta radiation. But, like all previous devices, it is still a point-type detection system.

One system that should provide a standoff detection capability is the IONDS which is under development. This system is supposed to detect and plot a nuclear burst and automatically send a warning to the corps headquarters. It does not, however, measure radiation levels.

Other approaches that are being explored to provide standoff radiation detection capabilities involve the use of lasers and solid-state imaging techniques. Systems based on these technologies, if successful, may be available in the late 1990s.

A couple of possibilities are on the horizon for personnel dosimeters. For example, the IM-185 dosimeter will measure both gamma and neutron radiation doses at the necessary minimum levels and should be fielded soon. In addition, the US Army has recently type-classified the DT-236 individual dosimeter to be worn on the wrist that will measure both gamma and neutron doses.

Currently available nuclear detection devices should be considered for incorporation into the LHX. The future development of nuclear detection systems should be followed, and those systems should be incorporated into the LHX when available.

d. Biological Agent Detection. Current doctrine for field detection of a biological attack depends entirely on human observation. Exact identification currently requires a complex, medical, laboratory-type assessment that precludes normal field use and may even be impossible in field laboratories. Currently, the only warning or detection of biological agent use is when an unusual number of animals or humans become sick. The major problem is the lack of a biological agent measurement technique or device that meets the requirements for field use. There are a number of ongoing efforts to resolve this problem. Figure 15 lists the ongoing efforts at this time.

System	Approaches	Status
Biological Remote Sensing Alarm	Detects clouds at a distance through laser fluorescent techniques.	Exploratory development.
Advanced Biological Detection Warning and Conformation System (ABDWCS)	Detects biological/toxins using a system of point detectors.	Concept exploration.

Figure 15. Potential future biological agent detectors.

Considering the LHX development schedule, it does not appear that effective, aircraft-mounted, biological agent detectors will be available at the beginning of the full-scale development phase. Provisions should be made, however, for incorporating biological agent detection in the LHX at a later date.

e. Detection Summary.

NBC weapons are expected on the future battlefield in relatively large numbers. Army aviation must be prepared to fight in that environment. NBC detection and warning systems are vital to the success of not only the LHX in the NBC environment, but the rest of the combined arms team as well. If the LHX crew is not provided with a detection capability, they will not know which areas of the battlefield are contaminated and, therefore, must fly in full NBC gear when the use of NBC weapons is suspected or exists in the battle area. In addition, when the LHX returns to a landing area or a forward arming and refueling point (FARP), the ground crew must assume the aircraft is contaminated and treat it appropriately. The capability of the LHX to perform reconnaissance missions will also be severely limited without onboard detectors. With NBC detectors on board the LHX, the crew can fly in partial NBC protective gear, thereby increasing the probability of mission success. The reconnaissance mission can be better accomplished, and the ground crew will have some indication of whether the aircraft is dirty or clean before it lands.

NBC detection devices available in the inventory and those under development do not currently meet all the requirements necessary to counter the threat. The need still exists for a better, all-encompassing NBC detection system that will provide prewarning at sufficient distances to allow aviation, as well as ground personnel, to take evasive and protective action. Until a standoff detection system is developed to meet that requirement, the LHX design should consider the utilization of current and proposed detection devices to provide the best interim detection system. That system should minimally include point detection devices both inside and outside the aircraft. The outside detector should alert the aircrew when they have flown into a contaminated area, identify the type of contamination, and measure the agent concentration. The inside detector should provide a similar alert and display accumulated dosage levels when contamination enters the aircraft crew station, troop compartment, or maintenance areas. The aircrew could then take the appropriate action to protect themselves and to provide a warning to the rest of the combined arms team. Limited testing has indicated that the use of current chemical point detectors can operate from an aircraft in flight.[3]

Additionally, programs to provide the LHX with a standoff detection capability should be given a high priority and, during the LHX full-scale development, the aircraft design should include provisions to incorporate standoff detection systems when they are available.

5. DECONTAMINATION.

a. General. One more NBC problem area that needs to be addressed is that of decontamination. The Warsaw Pact nations presently hold an advantage, in the number of troops and equipment, over the U.S. and NATO forces in Europe. Because of our disadvantage, all equipment contaminated by NBC weapons must, at some time, be decontaminated and returned to combat as quickly as possible. Consequently, aviation units and individual aircraft require some means of decontamination. The effectiveness of present decontamination methods available for aviation equipment and personnel is not sufficient to meet the future threat. Aviation units are afforded some decontamination capability but not sufficient enough to meet what is expected on the battlefield of the future.

b. Nuclear Decontamination. The threat imposed by nuclear radiation normally takes the form of radioactive particles that become imbedded or attached to debris disbursed by the initial blast, including particles of dust and dirt. The fallout of this debris covers terrain, equipment, and humans. Nuclear decontamination can be accomplished by three means--aging, sealing, or removing. Aging is simply a matter of waiting until the level of radioactivity has naturally dissipated to a level that is no longer harmful to humans. The sealing technique is one of covering the radioactive contamination with a substance like dirt or asphalt to contain the radiation and to prevent it from reaching and affecting personnel. Removing radioactive material from equipment is accomplished by washing or vacuuming the contaminated item. Generally, the inside of the vehicle can be vacuumed while the exterior is cleaned with air or water dispensed from high-pressure hoses. The major problem in using these approaches with vehicles is that they are time-consuming and labor-intensive. Additionally, when water is used, a large supply must be available on or near the battlefield. The waste or contaminated water and material must be collected and disposed of by burying it.

c. Chemical Decontamination.

Chemical decontamination can also be accomplished by removal, neutralization, weathering, or sealing. The types of equipment or kits available for applying these techniques are listed in figure 16.

As shown in figure 16, numerous problems exist when using current decontamination equipment or kits. The current chemical decontaminants DS2 and STB are corrosive and will remove the paint or protective IR coating from aircraft, can destroy the electrical and avionics equipment, aircraft materials, and will effect the visual properties of aircraft canopies. In addition, these chemicals necessitate special handling and storage and require the user to wear protective clothing. This leaves aviation units with the old standby of soap and water or the standard aircraft cleaner. Soap and water remove surface contamination on equipment and will neutralize some agents with time. It may be of some help on the outside of the aircraft but cannot decontaminate the aircraft crewstation or the avionics and electronics equipment areas. Another method for decontamination is aging. With time, most chemical

Device	Operational Use	Limitations
M11 Decontaminating Systems	Lightweight portable system used to decontaminate equipment exposed to liquid blister, nerve, or biological agents.	o Uses DS2, a corrosive material when applied to some metals and plastics. o Combustible. o Time-consuming. o Large quantities required for full decontamination. o User must wear protective clothing. o Exterior only.
STB (Decontamination Agent)	Used on equipment. Decontaminates all chemical agents and spores.	o Reacts violently with liquid mustard agents. o Combustible. o Corrosive to most metals. o Damages most fibers. o Large quantities required. o User must wear protective clothing.
DS2 (Decontamination Agent)	Used on equipment. Decontaminates all chemical agents.	o Corrosive to airframe and plexiglass. o Large quantities required. o User must wear protective clothing.
M12A1 Power-Driven Decontamination Device	Power-driven apparatus used for equipment decontamination or personnel showering. Can be used on aircraft with soap and water.	o Large amounts of water needed. o Labor-intensive. o Large, truck-mounted, 500-gallon device (2 1/2-ton truck). o Limited to field use. o Exterior only.
M13 14-Liter Portable Decontamination Apparatus	Manually operated device that dispenses standard chemical agent decontaminating solution (DS2).	o DS2 is corrosive. o Limited volume. o Exterior use only. o Personnel must wear protective clothing. o Time-consuming.

Figure 15. Chemical decontamination materials and equipment.[46, 47]

agents will dissipate. This decontamination method would, however, require that individuals who fly or work around the aircraft to be fully protected until the agent has dissipated. New approaches to decontamination are required. At the present time, there is no completely adequate method for the decontamination of Army aircraft.

Both the U.S. Army and the U.S. Air Force are working on the development of new decontamination systems (figure 17) that may be applicable to the LHX when they are fielded.

Device	Operational Use	Limitations
XM17 Lightweight Decontamination System (Sanator)	High-pressure, power-driven hot water/steam system can be used to dispense water-soluble decontaminating solutions.	o Large amount of water needed. o Weighs 360 lb. o Exterior only.
XM18 Skid-Mounted Decontamination Apparatus	Power-driven, high-pressure steam can be used for the dispersion of super tropical bleach (STB) or German C-8 Emulstion.	o Time-consuming. o Large amount of water needed. o Mounted on a 5-ton truck. o STB is corrosive on aircraft. o Labor-intensive. o Exterior use only.
C-8 emulsion	Decontamination of chemical and biological agents.	o Large amounts of water. o Exterior only. o Labor-intensive.
XM15 Interior Surface Decontamination (ISDS)	Portable (57-lb) unit that provides high-temperature airstream that vaporizes liquid/surface contamination compatible with aircraft interiors.	o Heavy for onboard storage on LHX. o Small capacity.

Figure 17. Equipment decontamination systems under development.[46, 47]

The XM17 and XM18 systems are dependent on the use of hot water and steam. Both require a readily available source of water. In addition, the XM-18 is relatively heavy and, therefore, has limited mobility. The contaminated aircraft must be brought to the decontamination device at some predetermined location.

The XM15 system uses a stream of hot air to decontaminate equipment and is somewhat smaller in size (57 lb). This system is considered compatible with the interior decontamination of helicopters but has not yet been fully tested. In addition, it requires a knowledge of the location of the contamination in order to be effective in a timely manner.

A number of additional research efforts are underway at the Chemical Research and Development Center (CRDC) to develop new chemical and biological decontaminants and decontamination systems that can be used on both the exterior and the interior of aircraft. Most of those systems will probably be available later than the scheduled date of the initial fielding of the LHX, but the LHX design should be prepared to incorporate these advances when they mature. One such CRDC/AVSCOM-developed system, designed for all aircraft, in the prototype stage (the Helicopter Self-Decontamination System) uses the helicopter's engine hot exhaust/bleed air to decontaminate the aircraft. The LHX design should make provisions that would allow the hot air source to be easily accessible for this purpose.

Attention to the design details of the LHX itself can do much to minimize the contamination of the aircraft and to reduce the need for decontamination. For example, if the interior of the LHX is protected from NBC agents by sealing and overpressurizing of the cabin, contaminated agents would not enter the aircraft in the first place. The need for interior decontamination would then be reduced. Application of the design guidelines developed by the CRDC to minimize contamination and to facilitate decontamination will further reduce the problems of decontamination.[48] The two-volume set of guidelines provides recommendations for the design configuration of equipment and vehicles that will help prevent the collection and retention of contamination and for materials that reduce the impact of contamination.

The use of chemical agent-resistant coatings (CARC) would also simplify the decontamination procedure by limiting the amount of an agent absorbed by the aircraft. Similarly, the U.S. Navy is developing a sacrificial coating that absorbs chemical agents. This sacrificial polymer coating can be easily placed over the present aircraft paint before the aircraft is exposed to chemical agents. When the agent and the coating come in contact, the agent is absorbed by the polymer coating. Both the coating and the agent can then be removed by washing the exterior with a water-based stripping solution.[36] The disadvantage of sacrificial coatings is the need to recoat the aircraft after it has been decontaminated.

d. Biological Decontamination. Biological agents that are released by aerosol and dry power will cover aircraft, equipment, and individuals. Once the commander suspects his unit has been subjected to biological agents, he can direct the aircraft and the equipment to be washed with hot soapy water, ionic detergents, STB, or a variety of disinfectants. The equipment and aircraft can then be placed in the direct sunlight. The sunlight will not only dry the wet equipment but will also tend to neutralize live biological agents. The problem with this approach is threefold. First, it is labor-intensive; second, it requires that the equipment and the aircraft be withdrawn from the battle for a number of hours; and third, soap and water and many disinfectants cannot be used on the interior of the aircraft.

e. Decontamination Summary.

During future conflicts, the LHX can be expected to fight within NBC contaminated areas. Effective contamination protective measures and decontamination methods are therefore required.

Current decontamination methods and equipment are not sufficient to provide the capability needed in future conflicts. The major problems associated with the current systems are their corrosive effect on both the exterior and the interior of the aircraft and electronics equipment and the amount of manpower and time required. New decontamination methods are under development but are not yet available.

The LHX design can do much to help alleviate the decontamination problem by the incorporation of the following:

(1) The CRDC design guidelines to minimize contamination effects.

(2) The design of an NBC, sealed, and overpressurized aircraft to prevent contamination from entering the aircraft.

(3) The use of chemical agent-resistant coatings to limit the amount of contamination that sticks to the aircraft surfaces.

(4) Provisions for the attachment of portable, hot air, decontamination devices that could be carried on board the aircraft.

6. CONCLUSIONS.

The evaluation of the threat in future conflicts indicates that Army aviation can expect to encounter and to operate within an NBC hostile environment. The Soviets have employed and will continue to employ NBC weapons. They are also well-prepared and equipped to fight an offensive conflict in that environment. The Soviets or Soviet-backed forces have reportedly used chemical weapons in Laos, Cambodia, and Afghanistan.

The current fleet of Army aircraft is not as well-equipped to operate in the NBC environment as required by future conflicts.[8] The aircrew is dependent on individual protective clothing to shield them from the toxic environment at the cost of considerable loss of combat effectiveness. There is a lack of detection devices to determine where contamination is located before entering those areas. Decontamination procedures are labor-intensive and time-consuming.

If Army aviation is to be successful in future combat as a member of the combined arms team, defensive measures must be applied to the LHX fleet of aircraft to reduce the impact NBC weapons have on mission effectiveness.

The four defensive measures for survival in the NBC environment include the use of medical pretreatments and antidotes, contamination avoidance, and personal and collective protection. Each has its distinct advantages and disadvantages which must be fully exploited to assure success of U.S. forces in future conflicts.

Medical pretreatments and antidotes, when applied immediately before or after a chemical or biological attack, can save lives. Unfortunately, they often have an adverse effect on the capabilities of soldiers to effectively continue the battle. Individuals will experience varying levels of incapacitation from hours to weeks.

Contamination avoidance appears to be the most effective means to prevent casualties and the debilitation of personnel during an NBC attack. In some cases, it will be a viable option. The LHX may be able to fly around the contaminated areas and still perform its mission. This option is, however, considerably dependent on the ability to determine where the contamination is located. To do so, the LHX must be provided with a reliable means to detect contamination. Contamination avoidance, unfortunately, cannot be exercised at all times. If the enemy is to be denied the terrain he wishes to occupy, the LHX must be prepared to fight in contaminated areas.

Collective protection, in which the LHX's interior is sealed and pressurized so that contamination cannot enter the aircraft, has the potential to provide both the crew and onboard systems and equipment maximum protection. The crew could then operate in a "shirt-sleeve" environment without the performance degradation imposed by NBC protective clothing and masks. The disadvantage of this approach is the possibility that enemy gunfire could penetrate the aircraft and breach the integrity of the collective protection system. In addition, there may be times when the aircraft must land in contaminated areas due to an emergency or to pick up and discharge passengers.

Individual protective clothing, worn by each crewmember in the LHX, will provide a life-saving function and will allow aviation missions to be accomplished at some degree of effectiveness. Current protective clothing appears to be adequate from the standpoint of providing NBC protection, but it imposes restrictions that severely degrade crew effectiveness, such as reduced visual capability, reduced manual dexterity and tactile sensitivity, and heat stress. The combat effectiveness of Army aviation in NBC protective clothing is considerably less than it would be in standard flight gear.

The solution for the LHX therefore appears to be a hybrid system that integrates the advantages of collective and personal protection. Such a system could allow the aircrew to operate in a sealed and pressurized aircraft partially or fully clothed in NBC protective gear. When the integrity of the collective protection system is maintained and the crewstation is contamination free, the aircrew could operate in partial NBC gear. When approaching a known contaminated area or when the aircraft detectors indicate the aircraft is in a contaminated area, the mask and the gloves could be donned to provide full protection. This approach would allow maximum crew effectiveness to be obtained when not in a contaminated area, as well as assured protection to the aircrew when in a contaminated area.

The LHX will also require NBC detectors both inside and outside the aircraft to inform the aircrew when they have entered a contaminated area and whether the contamination has penetrated the crewstation. Remote standoff detection devices are necessary to allow the LHX to successfully perform its NBC reconnaissance missions and to provide the aircrew an early warning so that the tactics of contamination avoidance can be used.

The design of the LHX must also include a crew station or individual microclimate cooling system to avoid aviator heat stress during flight in hot weather. Heat stress and the resulting crew fatigue are major contributors to the reduced capability in current aircraft.

The crewstation configuration, as well as its controls and displays, must be designed to overcome the restrictions of reduced visual capabilities, freedom of movement, and loss of dexterity and touch sensitivity imposed by wearing NBC protective clothing and life-support equipment.

Designing for ease of decontamination must also be addressed. Current techniques are labor-intensive and only partially successful. The collective protection provided by a sealed aircraft should reduce the decontamination effort by preventing contamination from entering the aircraft. The use of available and future contamination-resistant paints and coatings, coupled with design techniques that eliminate external and internal contamination collection points, are a necessity to reduce the manpower and time required for decontamination. The integration of a lightweight hot air decontamination system as part of the LHX design should further improve upon the decontamination capability.

Another important area that requires attention during the design of the LHX, with respect to the NBC environment, is the ground crew workload associated with maintaining, rearming, and refueling of the aircraft. Those activities rapidly increase in difficulty when wearing NBC protective clothing. Fuel ports, along with weapon compartments and mounting surfaces, need to be designed to allow for rapid rearming while wearing NBC gear. Considerable attention needs to be devoted to easily removing and replacing aircraft systems and components during maintenance activities.

The design of a hybrid NBC collective and personal protection system is well within the current state of technology, as defined in the AVSCOM Trade-Off Determination.[9]

The current technology in the area of NBC contamination detection is not as advanced. Remote standoff detection capabilities are in the early laboratory and concept phase of development and are not expected to be available until the late 1990s. These programs need to be given a high priority to accelerate their development. Currently available point sampling detectors are, however, available in ground systems. Improvements in those systems are also possible within the LHX time period.

Ongoing programs are in effect to improve the individual protective clothing and masks worn by the aircrew and ground forces. The LHX can take advantage of those programs early in their development by assuring they are not designed as separate items but include design features that allow them to become part of the LHX integrated crewstation. The aircrew integrated helmet and crewstation cooling systems are two examples of where the approach can be applied.

The use of collective protection, chemical-resistant coatings, and contamination-reducing configuration design techniques are currently available to aid in reducing the labor-intensive decontamination process. Decontamination equipment and systems that will allow for full interior and exterior aircraft decontamination are not yet available, but programs are underway to develop them. The LHX should make provisions for their incorporation at a later date.

7. RECOMMENDATIONS. The conclusions reached during this analysis support the following recommendations for incorporation into the LHX fleet of aircraft:

a. Protection System. A hybrid collective protection equipment system be provided for the LHX that includes a collective protection sealed and pressurized cabin, individual protective clothing and masks, and aircrew cooling by means of an environmental control system supplemented with an individual microclimate cooling system. The dual protection afforded by a hybrid collective protection system will prevent contamination from entering the aircraft, thus protecting the crew and aircraft equipment and systems from contamination. The individual protective clothing system will provide crew protection when the integrity of the collective protection is breached or the crew must leave the aircraft in a contaminated environment. The cooling system will reduce the impact of the heat stress problem associated with NBC clothing.

b. Decontamination. The labor-intensive and equipment degradation effects of decontamination should be reduced by incorporating collective protection, agent-resistant coatings, and contamination-reducing design techniques into the LHX system. Provisions should be made for incorporating onboard decontamination systems when they are available. Collective protection will prevent contamination of the interior of the aircraft. Agent-resistant coatings and design techniques will reduce the accumulated contamination levels both inside and outside the aircraft and will make decontamination easier. The provisions for the inclusion of improved decontamination systems into the LHX will provide more flexibility as to when and where the aircraft can be decontaminated when those future systems are available.

c, Detection Systems. In the near term, NBC point sampling detectors should be provided to monitor contamination both inside and outside the aircraft. Provisions for remote standoff detectors should be included in the LHX design so that those systems may be incorporated when their development is completed.

The outside point sampling detectors will tell the LHX aircrew when they have entered a contaminated area. This information will allow the aircrew to leave the area or to don their NBC protective gear. The LHX NBC reconnaissance mission can also be performed using outside detectors. The detectors inside the aircraft will indicate when the crewstation collective protection system integrity has been breached. Remote standoff detectors, when available, will warn the aircrew of a contaminated area and will allow them to take evasive actions. Remote standoff detectors would also allow the LHX NBC reconnaissance mission to be accomplished without entering the contaminated area.

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ANNEX R-X

HUMAN FACTORS ENGINEERING ASSESSMENT OF NAVIGATION SYSTEMS FOR THE LIGHT HELICOPTER FAMILY (LHX)

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Annex R-X to Appendix R

HUMAN FACTORS ENGINEERING ASSESSMENT OF NAVIGATION SYSTEMS FOR THE LIGHT HELICOPTER FAMILY (LHX)

R-X-1. The report, "Human Factors Engineering Assessment of Navigation Systems for the Light Helicopter Family (LHX)" is reproduced on the following pages. The report was prepared by Richard N. Armstrong of the Human Engineering Laboratory, Fort Rucker, AL.

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HUMAN FACTORS ENGINEERING ASSESSMENT OF NAVIGATION SYSTEMS FOR THE LIGHT HELICOPTER FAMILY (LHX)

Prepared by:

Richard N. Armstrong

U.S. Army Human Engineering Laboratory

15 May 1985

HUMAN FACTORS ENGINEERING ASSESSMENT OF NAVIGATION SYSTEMS FOR THE LIGHT HELICOPTER FAMILY (LHX)

A. INTRODUCTION.

Successfully accomplishing high mobility Army aviation missions on the battlefield of the future depends on the capability of aviators to navigate their aircraft to a predetermined geographical point, with a reasonable degree of accuracy, within a precise period of time. To win the battle, aviation assets must be at the right place at the right time. Missions must be accomplished during the day and at night, as well as under adverse environmental conditions. Once at their battle position, crewmembers must be able to inform others of their location and the location of the enemy. The aircrew must also be able to report friendly and enemy activity observed while flying to the battle position.

Dead-reckoning techniques, using aircraft speed, heading, and time traveled were the mainstay of Army aviation navigation during combat for many years. More recently, that approach has been partially replaced by Doppler and Inertial navigation systems that use electromechanical sensors, coupled with electronic computers, to determine the aircraft's position and monitor movements over the ground.

The capability of Army aviators to effectively navigate on the modern battlefield is influenced by two major factors: the accuracy of navigation sensors and the method used to present or display navigation information to the aircrew.

The accuracy of available fielded sensors, although slowly improving, has not yet reached the point to where the aviator places complete confidence in these systems. As a result, aircrews rely on the use of paper maps on which they manually trace their position over the ground by comparing what they see outside the aircraft with the features depicted on the map.

Technology advances are expected to improve the accuracy of the navigation systems through the use of improved sensors and satellites located in space. The increased accuracy promised by those systems is necessary and will certainly be welcome by Army aviators. Improved accuracy will greatly increase the combat effectiveness of aviation assets.

The second factor to consider, how the information is accumulated and presented to the aircrew, also requires improvement if the full effectiveness of Army aviation is to be realized on the future battlefield.

The aircrew must not only have the capability to fly from one point on the battlefield to another but must accurately accumulate, record, use, and transmit position information concerning the threat and friendly elements encountered en route and while in the primary mission area. The task of combat navigation, therefore, includes more than the ability to accurately fly the aircraft from one location to another. Mission success also requires the crew to maintain an overall awareness of the rapidly changing tactical situation around them. Situation awareness includes knowing the geographic location of your own aircraft as well as the relative position of other members of the friendly combined arms team, the location of the threat ground and aviation forces, and where the man-made or natural environmental obstacles are positoned. The design of future Army aviation aircraft navigation systems must take into consideration all of these factors.

The purpose of this analytical assessment is to review current and proposed navigation systems regarding aircrew workload and mission effectiveness and to examine the capability of those systems to meet the needs of the future fleet of light helicopters (LHX). In order for the LHX to be operationally successful, the deficiencies of current navigation systems as outlined in the Army Aviation Mission Area Analysis (AAMAA) must be corrected. The major navigation shortcomings noted in the AAMAA[13] were:

(1) The aviator's visual attention required for navigation is too high.

(2) Spatial disorientation during flight is too frequent.

(3) Accuracy of current navigation systems is too low.

(4) Aircrew time and workload devoted to the navigation task is too high.

If the full potential of the LHX fleet is to be realized, navigation systems and techniques must have improved accuracy, while reducing the amount of time that the crewmembers must spend attending to the navigation task. Navigation systems for Army aircraft that are expected to be effective on the future battlefield should have the following characteristics:

(1) Provide real-time, accurate, spatial information concerning aircraft position during day, night, and adverse weather conditions.

(2) Allow the aircrew to rapidly obtain needed information from the navigation display with minimal visual attention inside the cockpit.

(3) Provide the capability for the aircrew to rapidly annotate the navigation display, during preflight planning, with information like the planned navigation profile, waypoints, known threat locations, location of friendly forces, obstacles, and hazards.

(4) Provide the capability to rapidly annotate the navigation display, with information concerning enemy and friendly forces, as well as points of interest discovered during flight.

(5) Provide a means for the aviator to easily transfer information noted in flight to other members of the combined arms team.

(6) Provide a fully organic system that does not radiate electronic signals which can be detected by the enemy and is independent of electronic ground references.

(7) Be low in weight and cost.

There are seven current candidate navigation approaches for the LHX aircraft:

Standard map system

Doppler/numeric display navigation system

Projected map displays (PMD)

Remote map readers

Automatic map reader

Graphic display navigation system

Computer-generated map displays

Each of these approaches possesses unique capabilities and attributes. The advantages and disadvantages of each of these systems are examined in the following analysis.

B. STANDARD MAP SYSTEM.

Traditionally, navigating an aircraft in a combat situation has been done by using hand-held paper maps supplemented by the aircraft heading and airspeed indicators, a clock or watch, and the aviator's knowledge or familiarity with the surrounding area. The aviator's familiarity with the surrounding area, more often than not, is the significant factor in effective navigation and mission success.

Situation awareness is obtained by the aircrew annotating their hand-held paper map with the desired flight profile, hazards they may encounter along the way, and the location of friendly and enemy force information. While the traditional method of navigation has served Army aviators satisfactorily in the past, when flying well above the terrain, it has severe limitations when considering the increased threat capability and the complexity of future combat.

Aviators flying at relatively high altitudes--hundreds of feet or more above the highest obstacles--are provided an overall visual perspective of the terrain and significant landmarks or checkpoints which allows them to easily verify the aircraft's geographical location (figure 1). They see the terrain through the aircraft windscreen as it appears on the map. Terrain flight tactics, now necessary to avoid detection and acquisition by the enemy, on the other hand, require the aircraft to be maneuvered as close to the earth's surface as possible. The aircrews must fly their aircraft close to the earth at altitudes that vary from a few feet to a few hundred feet above the ground. During nap-of-the-earth (NOE) flight, they are constantly maneuvering around or over trees, hills, and other obstacles. The same terrain, vegetation, and man-made objects that offer concealment from the enemy during terrain flight also limit the aviator's view of the surrounding area and navigational landmarks. The aircrew is suddenly deprived of the overall visual perspective available at higher altitudes and in its place is a much narrower and more limited field of view (figure 2). The pilot's view of the terrain surrounding his aircraft is changed from one that resembles the neatly layed out map that he uses as a reference to one that restricts his field of view to a few hundred meters or less in front of and to the side of his aircraft. His long-range horizontal or plan view of the surrounding area is now replaced with a short-range vertical view in which he can only see as far as the next obstacle (tree, hill, or building). Consequently, the task of navigating at low altitude is more demanding than navigation at higher altitudes and requires continuous comparison and interpretation of the terrain features with a hand-held map.

Figure 1. Aviator's view of the terrain during flight at altitude.

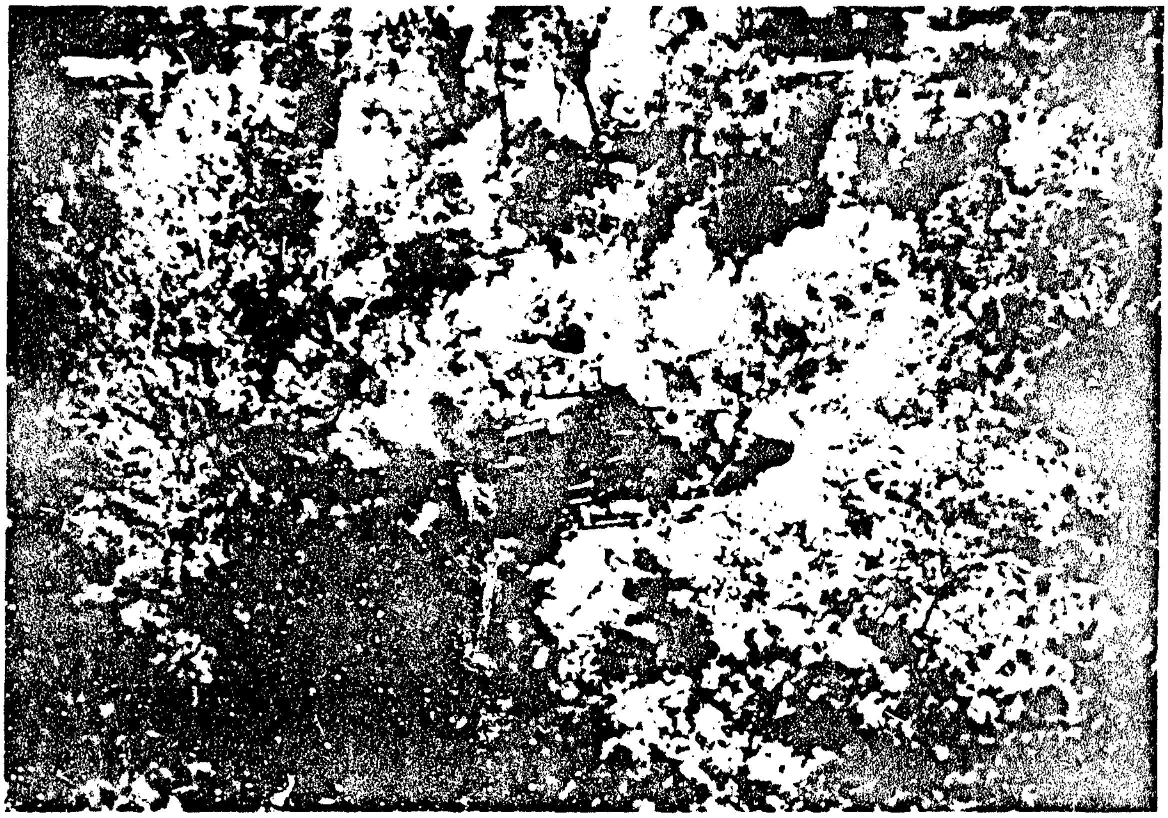

Figure 2. Aviator's view of the terrain during NOE flight.

Due to the aviator's limited view at low altitudes, the probability of disorientation and the difficulty of navigation increases considerably when flying in unfamiliar terrain, at night, or under conditions of low visibility. Daytime terrain flight is considered to be 1.3 times more fatiguing than that of a standard day flight. At night, the relative fatigue factor for terrain flight increases to 1.97 times normal day flight.[12] Nonetheless, in order for the Army to maximize its aviation assets, aviators must be able to effectively navigate under those adverse conditions.

The results of a series of navigation evaluations support the conclusions that the traditional navigational techniques (hand-held maps) are not adequate for NOE flight.

During a photographically simulated NOE study, experienced aviators were presented visual pictures of terrain features and asked to locate those features on the map depicting terrain relief information.[1] Their average success rate was around 37 percent. Similar results were obtained when pilots were asked to view a film of an NOE flight profile, follow that same profile on the hand-held map, and correctly identify the checkpoints at which the aircraft had stopped. The average checkpoint location error was 500 meters with some errors exceeding several thousand meters.

Similar results were again reported in a second study designed to evaluate the aviator's ability to recover from geographic disorientation by the use of a brief unmasking or "pop-up" maneuver.[2] In that study, the average error, for the 28 experienced Army aviators in the simulated "pop-up" task, ranged from 314 to 2,831 meters.

The results of a UH-1 dual-crew flight study[3] concluded that the probability of the aviator's ability to identify specific checkpoints while flying NOE was around 85 percent and the probability of locating a given landing zone within 100 meters was 77 percent.

When pilots were asked to simultaneously fly and navigate an OH-58 helicopter (one crewmember) over an unfamiliar NOE course at Fort Rucker, AL, 9 of the 10 aeroscout pilots became disoriented and failed to successfully navigate the course.[4] During that same assessment, it was found that the aviators were spending about 62 percent of their visual time outside the cockpit and approximately 14 percent looking at the hand-held map.

In two similar NOE flight studies, the attention devoted to various elements of the navigation task in a UH-1 helicopter was evaluated.[5,6] In those evaluations, the copilot, when assigned the task of acting as a navigator, while still performing his normal in-flight duties, spent around 49 to 57 percent of his visual time looking outside the cockpit and about 35 to 39 percent looking at the hand-held map. Although not directly related to physical workload, the results do point out that a large amount of the aviator's visual attention is devoted to the navigation task while flying at low level and NOE.

These reported evaluations were conducted under ideal, normal daylight conditions. During combat missions under less than ideal conditions, one can expect this problem to be amplified. The findings of the series of studies discussed above suggest that the traditional means of navigation are much too time-consuming and inaccurate to meet the challenge of NOE flight.

The use of a hand-held map as the major source of geographic information does have some advantages. First, the paper map is relatively easy to reproduce and distribute in large quantities. Second, the aviator can annotate the map by writing or drawing the planned mission profile directly on the map. Information concerning enemy and friendly forces, navigation aids, or hazards can also be easily placed on the map during mission preplanning. During the actual flight, overall information concerning the current situation can be added or old information modified relatively easily. Third, upon completion of the preflight, the aircrew can carry the map into the operations room and share it with others within the unit and pass it on to all other interested parties.

The paper map also has inherent limitations. Current map designs are a compromise between the requirements for various members of the combined arms team and other branches of the military services. Due to those conflicting requirements, the standard map does not contain the optimal information for Army aircraft flying at NOE. In many cases, they contain unnecessary information which clutters the map and makes it more difficult to use.

The navigational problems with hand-held maps are amplified when considering the goal of designing a single person crewstation for future Army aircraft. In most of the actual flight evaluations discussed above, the crew size consisted of a pilot and copilot, with the copilot assuming the role of navigator. Under those conditions, most of the copilot/navigator's visual time was consumed with the navigation task during the flight. In addition, when a single aviator was asked to assume both the pilot and navigator roles, mission success decreased to about 10 percent. The likelihood of a single crewmember effectively assuming the roles of both the pilot and copilot, while flying NOE over unfamiliar terrain, using the traditional navigation approach therefore appears to be virtually impossible in the future combat environment.

C. DOPPLER/NUMERIC READOUT NAVIGATION SYSTEM.

One approach to ease the workload and increase the accuracy of navigation during terrain flight is to use an electronic Doppler navigation system. Some Army aircraft are currently equipped with such systems, designated the Lightweight Doppler Navigation System (LNDS), AN/ASN-128 (figure 3). This system is designed to provide position information accuracies in the range of 25 to 250 meters. The system measures the difference in frequency of a radio signal emitted by the LDNS and the returning signal reflected off some object or the ground slightly ahead of the aircraft. A computer then uses that difference along with information concerning aircraft heading, roll, and pitch to compute aircraft velocity, present position, and steering information. The computed navigation information is then provided to the aviator by means of numeric displays on the LDNS control panel. The LDNS control panel also includes an alphanumeric keyboard that allows the operator to program the computer with position and steering information of 10 predetermined destinations or checkpoints.

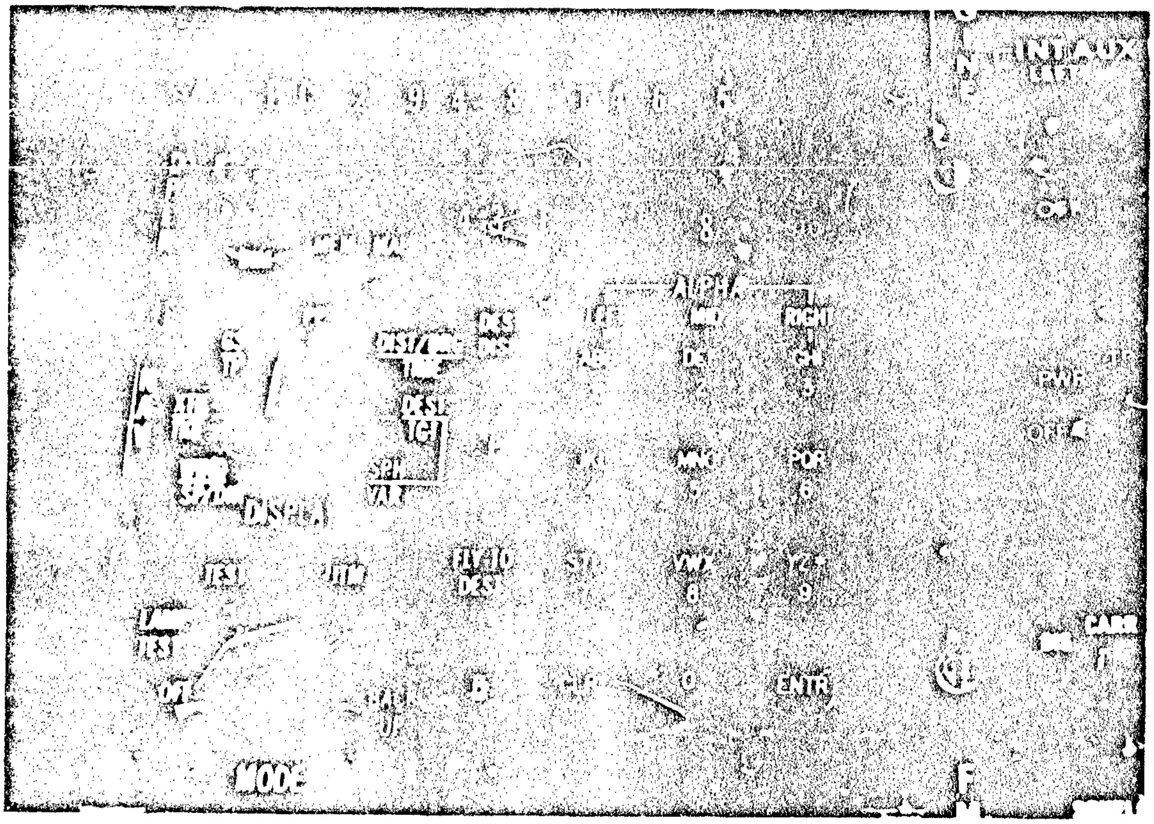

Figure 3. LDNS control/display panel.

When using the AN/ASN-128, the aviator typically navigates by obtaining the required information from the 13-digit numeric display in the cockpit, mentally converting that data to standard map coordinates, finding the coordinates on his hand-held map, then determining the relationship between the reference point on the hand-held map and the terrain features visually observed through the cockpit windscreen. The major part of the aviator's workload in performing this task is perhaps the mental processing of the data, the visual attention required to cross-check the system data with the outside terrain, and the operation of the alphanumeric control/keys when entering data in flight. The workload with this type of navigation system appears to be an improvement over the traditional method, but still falls short of providing maximum effectiveness when flying NOE.

During the operational test (OT) II of the AN/ASN-128 in the dual-crew AH-1S Cobra helicopter[11], a comparison was made between aviators navigating with the LDNS and navigating with a hand-held map. The results indicate that an NOE course can be traversed more rapidly with the LDNS and the aviator workload during flight is reduced. In addition, the LDNS requires less pilot-to-copilot communications during flight than hand-held maps require.

Two other evaluations conducted at Fort Rucker,[5,7] reported that with the LDNS/map combination, NOE and contour flight missions were flown in 15 to 25 percent less time than was the case with the hand-held map alone. In addition, disorientations experienced with the LDNS were 35 to 70 percent less than those found when navigating with the hand-held map. Visual attention measurements, observed during one of the above studies, indicated that when using the LDNS, the pilot/navigator spent 31 percent of the time viewing the navigation system and 49 percent looking outside the cockpit. As with the hand-held map, a substantial amount of the copilot/navigator visual attention was focused on the navigation tasks.

Although it is better than the hand-held map navigation approach, the AN/ASN-128 navigation system does have a number of distinct disadvantages. First, the workload prior to flight is increased due to the necessity to preprogram the system. Information concerning the preplanned flight path and associated waypoints is manually entered into the system by the aircrew before leaving the ground. Second, the degree of accuracy obtained with the LDNS is still heavily dependent on the aircrews' frequent updating of the system, by comparing the Doppler readout with checkpoints on the ground and the hand-held map. The aircraft must be maneuvered near or over the checkpoint on the ground approximately every 10-15 minutes to accomplish that updating. The third problem associated with LDNS is the requirement for the aviator to mentally interpret the digital readout of the Doppler display and locate the equivalent aircraft location on the hand-held map.

The navigation approach using the LDNS, supplemented with a hand-held map, is better than the traditional method of just using the hand-held map. The flight path can be covered in less time and the copilot/navigator visual attention requirement appears to be reduced. On the other hand, the workload for a two-member crew is still high and navigation accuracy is still less than that required for maximum mission effectiveness of the LHX during future conflicts. The likelihood of a single crewmember effectively performing the combined task of the pilot and copilot/navigator while flying NOE over unfamiliar terrain with the current LDNS/map system during NOE flight is extremely low.

D. PROJECTED MAP DISPLAYS/REMOTE MAP READERS.

Projected map displays (PMD) used with navigation sensors provide another approach for improved navigation in Army aircraft. Such map displays, using stored information on 35mm film cassettes, project the map image onto a small screen normally mounted in the instrument panel in front of the aviator (figure 4). The PMD uses input from a Doppler sensor and the aircraft flight instruments to compute position information which is superimposed on the map-like display. The PMD allows the aircraft course and position to be automatically traced on the map display thereby relieving the aviator/navigator from this task.

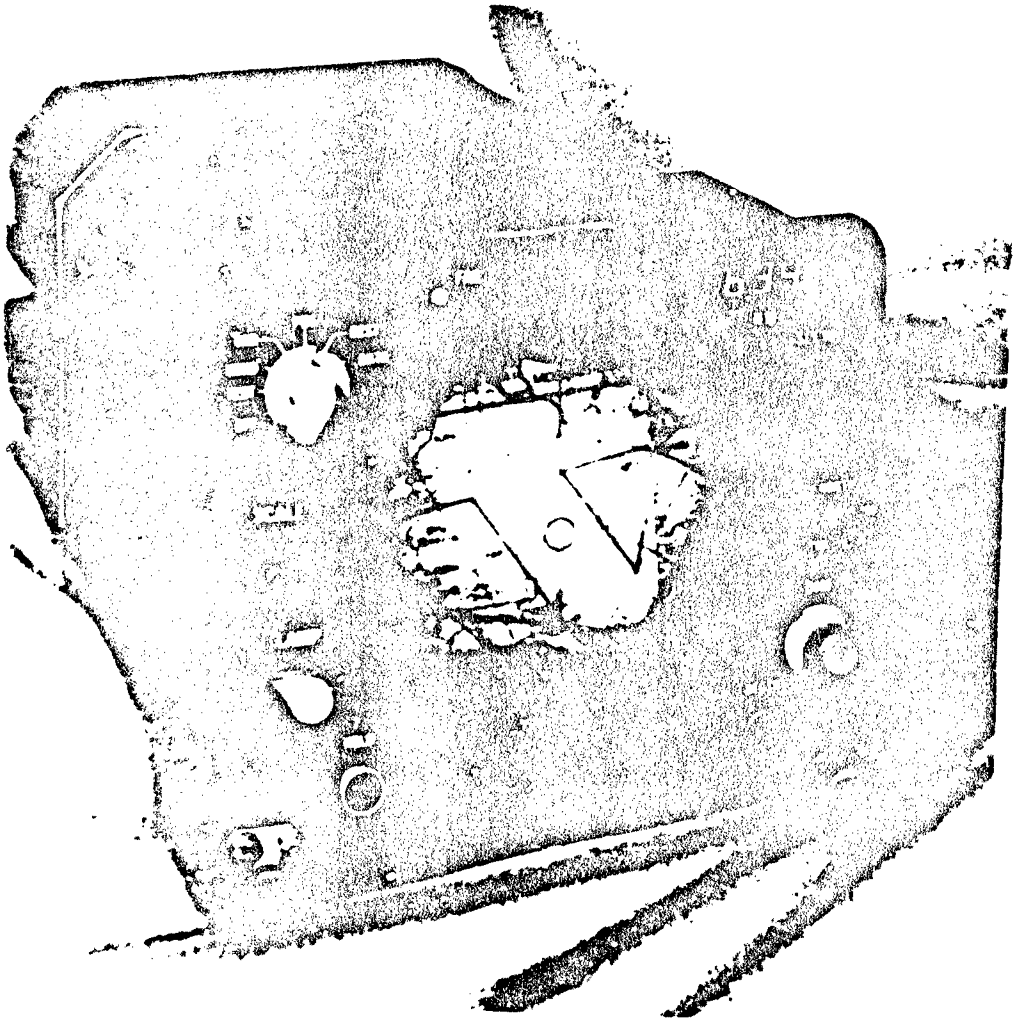

Figure 4. Projected map display.

A navigation assessment conducted at Fort Rucker has demonstrated that navigation performance is improved when pilots use a PMD[7]. During that assessment, the navigational effectiveness of dual-member aircrews was compared for three navigation systems, during the day and at night over several terrain flight courses in UH-1H and UH-1M helicopters. The aviators performed the navigation tasks using either:

(1) A standard map.

(2) A Doppler navigation system with numeric displays and a standard map.

(3) A PMD with input signals from the Doppler sensors and the standard map as a secondary reference.

During the day, NOE, and low-level flights, 20-kilometer (km) courses were traversed more rapidly with the PMD. The results indicate that navigation with the PMD required about one-half of the time experienced when using the hand-held map and about 60 percent of the time experienced using LDNS/map combinations. Pilots reported that there was also a significant workload reduction when using the PMD. In addition, the aircrews did not experience disorientation while using the PMD. A number of disorientations were, however, experienced with the hand-held map (10) and LDNS (15).

A more recent evaluation of the same three types of navigational approaches reported similar results.[5] In that evaluation, the copilot of a UH-1 helicopter performed the navigational task, while the pilot controlled the aircraft and flew where the copilot directed. The results indicate that when navigating with the PMD, the course was traversed in about 82 percent of the time used with the hand-held map. The average flight time with the PMD was about 96 percent of that with the LDNS, somewhat different than the improvement reported in the earlier test above. The study also found that there were fewer course delays and aviator disorientation when using the PMD. In addition, the aviator's visual attention devoted to the PMD navigation system (28 percent) was less than that experienced with the hand-held map (35 percent) or LDNS (31 percent). This allowed the copilot to spend more time looking outside the cockpit as compared to the other two systems. The navigational communications between the aircrew were greater with the hand-held map than with either of the other two systems, but the LDNS system required the least amount of communications.

The overall results of the two evaluations reported indicate that a navigation system using a PMD has a distinct advantage over the hand-held map and Doppler/map systems. When using the PMD, the mission course was covered more rapidly, the aviator's visual attention devoted to the navigation system was less, and fewer course disorientations and delays were experienced.

The major reported disadvantage of the PMDs tested was the lack of a capability for the aviator to annotate the display. The display is projected from a filmstrip that the aviator cannot write on like he does the paper map. A second disadvantage was the necessity to mount the entire system electronics, optical projector, and display in the already limited space of the crew station.

A third disadvantage of the PMD is similar to that of the paper map. Paper maps often contain information that is not necessarily pertinent to the navigation needs of Army aircraft in terrain flight. Too much information tends to clutter the display, making it more difficult for the aviator to rapidly obtain required information from the display. Since the projected map display originates with the paper map, the problem is carried over to the PMD.

A number of avionics contractors have recently overcome two of the above shortcomings by introducing remote map readers. The remote map reader replaces the crewstation's mounted, projected optical components of the PMD with a system located elsewhere in the aircraft. The output of the remote map reader is a standard color or black/white video signal that can be placed on a multifunction display in the crewstation (figure 5). Navigation symbology and waypoints, as well as threat and friendly force information can then be superimposed on the map display. Thus, the aviator can annotate the navigation display through a computer interface before and during flight.

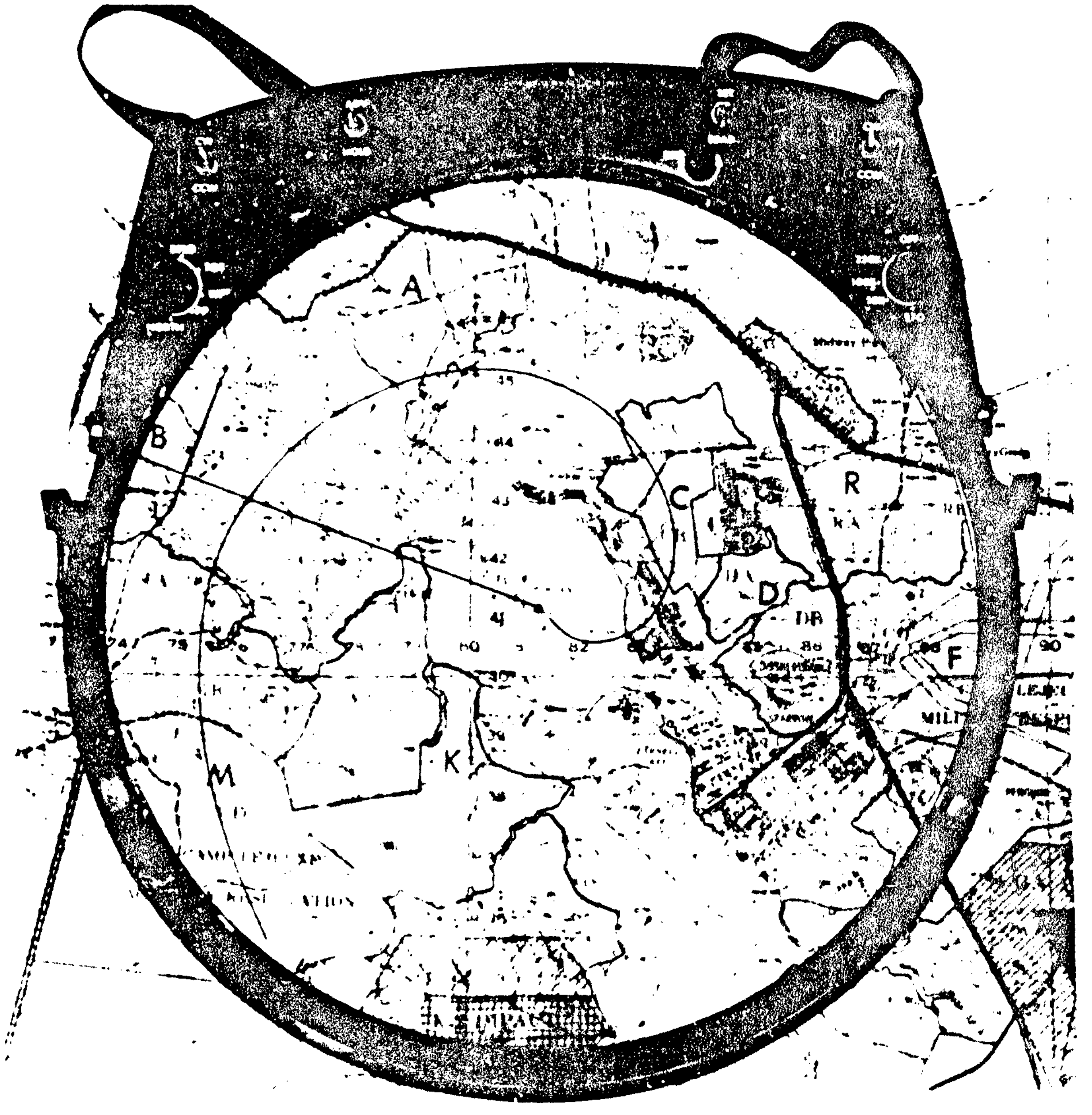

Figure 6. Automatic map reader.

The major disadvantage, much like the paper map, is the requirement for aviators to hold the automatic map reader in their lap during flight. The accuracy of the system is not only dependent on the input of the Doppler navigation system, but also on how well the aviator aligns his paper map with the map reader. The automatic map reader has considerable potential for improving navigation in existing aircraft that have Doppler sensor or similar position measurement sensors. When examined in light of the increased accuracy and reduced workload requirements for small crew stations of future lightweight aircraft, the automatic map reader is not considered a very viable option, especially in a single-crew cockpit.

F. GRAPHIC NAVIGATION DISPLAYS.

Another feasible approach for displaying navigational information in future Army aircraft is the graphic navigation display system similar to the one provided for the Army's new scout helicopter (OH-58D). This system combines the input from an updated Doppler navigation sensor system with a graphic display to provide the pilot with navigational information on the aircraft's multifunction displays (figure 7). The system reportedly will be more accurate and have the capability to store more waypoints than the currently fielded LDNS.

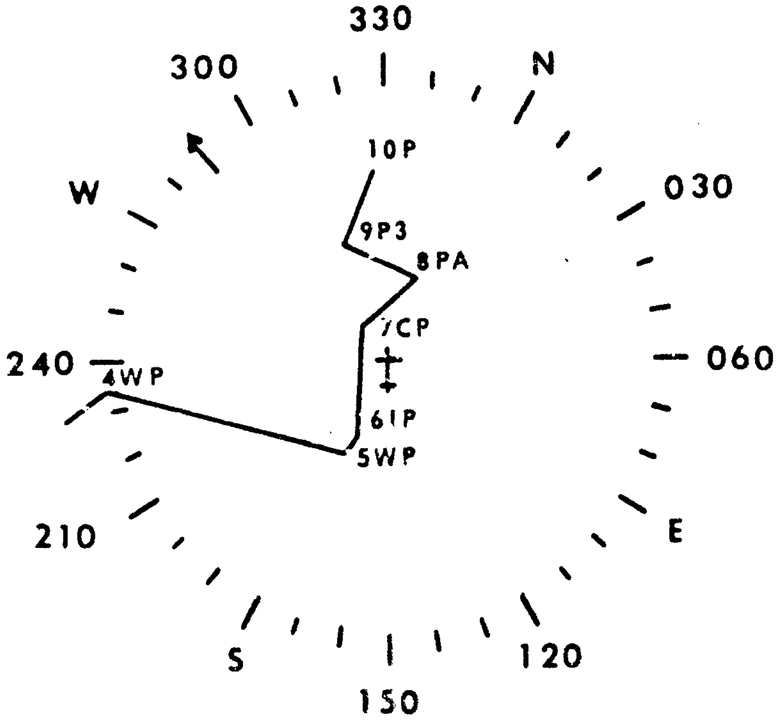

Figure 7. Graphic navigation display.

The graphic navigation display approach provides a display that is uncluttered with nonessential information and allows the aviator to rapidly determine his relative location with respect to this planned flight path. The aviator must, however, still mentally translate the graphically displayed information and relate it to a geographic position on a paper map.

Preliminary results of the recently completed development test on the OH-58D indicate that the graphic display approach is superior to navigation with the traditional hand-held map.

Crewmembers (dual crew) were able to navigate an NOE flight course in about half the time when using the graphic display system and a hand-held map than when using a standard map alone. It should be noted, however, the course flown during that testing consisted of relatively flat, open, and rocky desert terrain.

The OH-58D navigation system, which includes a Doppler with an updated heading reference system, like its predecessors, still requires periodic updates at 10- to 15-minute intervals. The update technique requires the aircrew to fly over a predetermined waypoint, already stored in the computer memory. If the aviator chooses to update the system by using terrain features or waypoints not already placed in the computer memory, those features must be manually entered into the system during flight.

The tests discussed above were conducted with a two-crew aircraft in which the pilot flew the aircraft while the copilot/observer performed the navigation task. The navigator used a hand-held map to confirm that the actual location of the aircraft was, in fact, what the navigation system was reporting it to be and to assist in system updating.

The limited testing of the OH-58D graphic display navigation system indicates it would be an improvement over the traditional approach to navigation. The mission can be flown faster and with more accuracy when using the graphic navigation display; however, it still requires a second crewmember to refer to a hand-held map to validate that the systems location information is correct. Without the hand-held map, the aircrew could not be sure the system is providing the correct information. In addition, the hand-held map allows the crew to maintain a situational awareness they would not otherwise have. The graphic display appears to be a viable option for a two-crew aircraft, but not for a single-pilot aircraft. Unfortunately, test data do not exist that compare the graphic display with the FMD or LDNS navigation systems.

G. DIGITAL GENERATED NAVIGATION SYSTEMS.

The latest technology in navigation systems involves the use of computer-generated maps and displays. The Defense Mapping Agency (DMA) has the capability to digitize terrain elevation and planimetric data that can be placed in the memory of an onboard aircraft flight computer. The flight computers, supplemented with aircraft movement information from sensors like those used in the Doppler navigation system can, in turn, produce a map-like image on a multifunction display in the crewstation. A number of avionics contractors have ongoing programs to design, evaluate, and provide digital-generated navigation systems. One such system is the night navigation and pilotage system (NNAPS)[9] under development by the Army Avionics Research and Development Activity (AVRADA) (figure 8). These systems have the <u>potential</u> capabilities to:

(1) Generate a digitally-based topographic map.

(2) Integrate inputs from aircraft navigation sensors and flight instruments to dynamically plot the aircraft position during flight.

(3) Automatically update the navigation sensor data using terrain correlation techniques.

(4) Provide a horizontal situation map display.

(5) Provide a vertical situation view of simulated terrain.

(6) Allow the user to annotate the map display with locally obtained information (wire/obstacles, enemy/friendly forces, and checkpoints) before the flight.

(7) Allow the user to annotate the map display during flight and store that information in computer memory.

(8) Allow the user to select the type and amount of information to be displayed (declutter).

(9) Provide the capability to calculate and display information concerning the unobstructed line of sight or intervisibility between the aircraft and other objects.

Figure 8. Digital map display horizontal view.

The replacement of the map in the crewstation instrument panel, similar to that of the PMD, in itself is a significant improvement but only one application of the full potential of the digital data base. The capability of the aircrew to interact with the display and data base is equally important. With a computer-generated navigation display, the aircrew has the potential to optimize the displayed information to meet the changing mission requirements. The map scales may be changed as desired. The aviator can change the map display orientation to one that fits the mission. Horizontal or vertical views of the terrain may be selected as desired and information concerning threat and friendly forces could be overlayed on the display to provide an overall awareness of the battlefield situation.

For example, the aviator could observe data from a horizontal viewpoint in which the displayed information is presented like that normally seen when looking at a standard map (figure 8). A perspective or vertical situation view of terrain ahead of the aircraft could also be selected. The displayed scene would look much like that observed when looking through the crewstation windscreen during low-level flight (figure 9). If desired, the scene could be moved ahead to assess the terrain obstacles and known threats over the next hill or obstacle. The flight plans, including threat information, can be overlayed on the vertical or horizontal display to make the aviator aware of the current situation.

Figure [illegible]. Digital map display vertical view.

Much like the PMD, the digital map could be annotated by a computer interface within the aircraft or a preplanning station in the unit operations center.

From the crewstation workload aspect, it is expected that the digital map display should be at least as effective as the PMD and hopefully more effective. Limited simulation studies have indicated the feasibility of placing the digital map display in the crewstation, but the workload or crew attention required has not yet been established. Simulation and flight evaluations of the system are expected to continue during 1985.

The effectiveness of the digital map navigation system is very much dependent on the existence and quality of the DMA-digitized topographic data base. Within the next decade, the Digital Land Mass System (DLMS) is expected to be used for the majority of the requests for digital mapping products.[10] The DLMS data base currently consists of the digital terrain elevation data (DTED) and digital feature analysis data (DFAD). The DTED specification provides terrain elevation data within a 130-meter horizontal circular error and ±30 meters vertical. DFAD provides radar significant feature data at similar accuracies. Radar significant features include objects with high contrast that can be detected by radar. Most area features must be at least 500 feet by 500 feet to be in the data base with the exception of some power lines and towers that have a bright radar signature. Information on drainage, vegetation, urban area, bridges, and power lines are currently available, but features like roads and railroads have not yet been incorporated in the data base. The current available data base does not appear to be comprehensive enough to completely meet Army aviation needs on the future battlefield. The DMA has an ongoing effort to improve the accuracy and expand the data base as requirements evolve. Those improvements are necessary if the full capability of the digital data base navigation systems is to be realized.

A second area of concern with a digital map system is the considerable computer memory needed to store and manipulate the data base during a typical mission. Significant improvements in flight computer processing capability will be required to allow all the potential advantages of the digital map technology to be effectively applied in Army aircraft.

Digitally generated navigation displays, if they operate as advertised, should be at least as effective as PMDs in providing map-like information to the aircrew. In addition, they should provide a capability to declutter the display and the option to view the terrain ahead from either a horizontal or vertical perspective. The annotation capability during preflight and flight appears to be equivalent to that of the PMD. One major advantage of the digitally-generated data base over the PMD would be in the area of automatically updating the navigation sensor information and automatic terrain avoidance. In theory, the digitally-generated data base could be used for that purpose, but based on the availability, accuracy, and content of the currently available data base information, that feature may not be available when the LHX is initially developed.

Limited simulation and analytical assessments indicate that digital map display systems do have the potential for providing the much needed navigation and situation awareness improvements, in both dual and single crew aircraft. The ultimate payoff for the LHX is considerable if technology reaches sufficient maturity within the LHX development. The flight hardware developed to date provides limited capabilities of a horizontal view of the terrain but not the vertical perspective. The true system advantages and any resultant impact in aircrew attention or workload cannot be determined until flight systems have been assembled and tested in the helicopter environment.

H. SUMMARY AND CONCLUSIONS.

The success of Army aviation on the future battlefield is much dependent on the ability of the aircrew to rapidly place their aircraft in the correct tactical location. Accurate navigation in mid- to high-intensity conflicts is extremely important in accomplishing a tactical mission. Studies and evaluations of the relationship between human performance and currently fielded navigation systems reveal a number of disparities that result in less than the desired level of mission success. This performance is due, in part, to a number of factors, including loss of perspective, map design, equipment sensors, and display designs. Evaluation of newly developed and available navigation systems indicates that those systems enhance the present capability to navigate on today's battlefield, but further improvements are needed if the maximum effectiveness of Army aircraft capabilities are to be realized.

Based on the data discussed in this analysis, the traditional hand-held map, the Doppler/numeric display systems and graphic display systems appear to be less accurate and require too much visual attention on the aircrew's part to provide the mission effectiveness necessary for the LHX fleet.

The PMD/remote map reader, which has been tested and flown in operational aircraft, improves upon the current systems by taking the traditional map information out of the aviator's lap and placing it on a display in the instrument panel of the aircraft. In tests conducted so far, an aircrew of two can navigate the mission terrain more rapidly with less required visual attention on the part of the navigator than was required with previous navigation systems. The system does, however, require much of the copilot/navigator's visual attention (28 percent) to monitor the progress along the flight path and update the system approximately every 10 to 15 minutes. This diverts much of the copilot/navigator's time from other mission tasks. This may not be a major concern in a dual-crew aircraft, but in a single crewmember aircraft, the visual workload associated with the navigation task would have a considerable impact on the mission effectiveness.

The digital map display, because of its inherent flexibility, provides greater potential for mission success in the LHX than the projected map system. This system has been tested in simulators but has not yet been flight tested. The visual attention required for the digital map system will hopefully be less than that with the projected map diaplay, but it is expected that the aircrew will still have to devote considerable time, with their head inside the cockpit, viewing and obtaining information from the panel-mounted digital map display. Again, in a two-crew aircraft, this is not as critical as in a single-crew aircraft. In the single-crew LHX, the visual workload associated with a panel-mounted navigation display could still have a considerable impact on mission effectiveness. The presentation of essential navigation data to the pilot in a manner that does not require bringing his eyes inside the crewstation should help reduce that impact. The optimal use of heads up and helmet-mounted displays and/or voice interactive devices to provide that information should be explored. In addition, if the digital map system is to meet its full potential, enhancing the accuracy and content of the available digital data base must be pursued to assure it is available for the LHX.

NOE navigation requires continuous orientation on the part of the flight crew by identifying terrain features along the flight path and correlating them with information on the navigation map or display. This is a formidable task, even under ideal conditions during the day, at night and during periods of low visibility, it becomes more difficult. The LHX, to be successful on the future battlefield, therefore requires a navigation system that will assure the aircraft will be at the right place at the right time. From the human factors viewpoint, both the remote map reader and digital map displays can provide an increased capability over current systems and appear to meet the minimum requirements for the dual-crew aircraft. The digital maps technology has the potnetial to provide the better system from a soldier-machine interface point of view due to its increased flexibility. For a single-crew LHX, the presentation of navigation information on a display in the aircraft could very well be too demanding on the part of the aviator's visual attention at terrain flight levels. While flying missions at terrain flight levels, the single crewmember should devote as much visual time outside the crewstation as possible. Navigation information should therefore be provided to the aviator in a way that allows him to keep his eyes outside the crewstation during that phase of flight.

If the goal for a single-crew LHX is to be accomplished, a high priority must be placed on the improvement of navigation sensor accuracy and the availability and accuracy of digital data base information. Simulation and flight test studies to specifically address the most effective means of providing navigation information to the aircrew are also needed to reduce the considerable amount of aviator attention now devoted to that task and enhance the LHX combat mission effectiveness.

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ANNEX R-XI

THE INTEGRATION OF VOICE AND VISUAL DISPLAYS FOR AVIATION SYSTEMS

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Annex XI to Appendix R

THE INTEGRATION OF VOICE AND VISUAL DISPLAYS FOR AVIATION SYSTEMS

R-XI-1. Reproduced on the following pages is the report: "The Integration of Voice and Visual Displays for Aviation Systems."

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THE INTEGRATION OF VOICE AND VISUAL DISPLAYS FOR AVIATION SYSTEMS

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SUMMARY

The unique visual requirements that occur when a helicopter pilot operates an aircraft at high speeds close to the ground requires that the cockpit designer reevaluate the traditional methods of information presentation. Current advances in cockpit display technology are in the direction of information being presented on multi-function cathode ray tube (CRT) displays which are accessed via key press input. Multi-function displays enable cockpit designers to design systems that present much more information while using less panel space than required for conventional analog instruments. This increase of presented information, coupled with the manual access requirement, can overload the pilot's visual and motor channels.

A current approach to the problem of potentially overloaded visual and motor channels is to use voice output and voice input technology to supplement visual output and motor input. There is the potential for less than optimal voice technology implementation unless care is taken by cockpit designers. In addition, there are several unique problems that arise when information is presented simultaneously in two modalities (visual and auditory). The issues that surround the use of multi-modal information displays should be researched carefully so that their implementation in the cockpit does not result in increased pilot workload. In this paper we discuss the evolution of cockpit displays, and how voice technology might best be employed to reduce pilot workload. A brief summary of some of the research conducted in our laboratory examining the integration of these multi-modal displays will also be presented.

INTRODUCTION

A pilot can be considered both a systems coordinator and a flight path manager. More specifically, a pilot is a decision maker. The pilot receives input from the aircraft systems (in the form of displays and gauges), the outside world (what is seen through the windscreen), and the vehicle dynamics (tactile, vestibular, and proprioceptive feedback), and processes this information. Outputs, in the form of control manipulations, are the result of the decisions made with regard to these three sources of input. The pilot's output, of course, changes the three sources of input, thus creating an "information processing loop".

The result of restricting the information that the pilot receives from any of these sources of input is fairly predictable. If any of the sources are degraded the pilot will try to maintain the same level of information input by attempting to extract additional information from the remaining sources. For example, a pilot suddenly flying into adverse weather will quickly switch his attention from the outside scene to the instruments. Conversely, a pilot descending to Nap-of-the-Earth (NOE) altitudes and flying at high speeds will tend to concentrate almost totally on the outside scene so as to avoid obstacles, and of necessity ignore the instruments. In the extreme, with no instruments or outside scene, a pilot will rely on the vehicle dynamics input and fly "seat of the pants".

One of the most rapidly changing areas of new aircraft design has been the cockpit. From very early simple cockpit layouts, the amount and types of information presented to the pilot have increased dramatically. There have been two main reasons for this proliferation of cockpit information: the availability of new display technology and the development of aircraft that had to be flown closer to the edges of their design envelopes to accomplish their missions. Modern high performance military airplanes are much less forgiving than the biplanes with which we began the aviation age; the modern aircraft requires more detailed control on the part of the pilot because the margin for error is so much smaller. Therefore, as the aircraft performance ranges began increasing there was a need for more and more information, thus more and more for the pilot to process.

One attempt to address the problem of more information being presented in the cockpit was to increase the crew size. The trans-oceanic Clippers of the late 1930's and 1940's had a crew of five, therefore more eyes in the cockpit. On the other hand, the modern B-747 has fewer crew members but has what appears to the non-pilot as a baffling number of dials and switches. However, many of the aircraft system indicators have been reduced to warning bells, buzzers, and lights. This represents a second attempt to address the problem: reducing the level of detail and the information output mode while still increasing the total number of systems for which information is <u>available</u> to the crew. This second attempt led to a proliferation of alert indicators, an increase from 300 to 750 from the B-707 to the B-747 (Veitengruber, Boucek, and Smith, 1976).

The requirement to have more information available to the pilot coupled with the lack of additional cockpit real estate has culminated in the type of cockpit that is found in the F-18. This "state-of-the-art" cockpit has three multi-function CRT displays, an array of light emitting diodes, and very few conventional gauges. A potential problem with multi-function CRT displays is that rather than just having to remember where to look on the panel for the appropriate information that he might want, the pilot must first remember a code sequence and then enter the correct key presses to obtain the needed information on the display. In the case of the F-18 there are over 675 three letter acronyms that can appear on the CRTs. The Nighthawk version of the Sikorsky UH-60, developed for the USAF by IBM, has brought the F-18 cockpit technology into the rotary wing area. In both cases, visual clutter has been reduced, but at the expense of a large increase in "cognitive clutter".

Pilots have usually been able to adjust to the changing sources of input: new cockpits, new and faster airframes, more demanding missions. The military solution to the changing information processing requirements has been to improve pilot training. We are now, unfortunately, approaching the point where the pilot; rather than the hardware, is becoming the limiting factor in mission success. In particular, current helicopter missions often involve low altitude, high speed flying, following terrain below tree top level and through valleys rather than over them. This type of mission is called Nap-of-the-Earth (NOE) flying. NOE flight is demanding under the best of climatic conditions and extremely demanding when attempted under conditions of night, adverse weather, or enemy threat. Because the pilot at the controls is primarily concerned with avoiding the obstacles that surround the aircraft he has little spare visual processing capacity for monitoring the aircraft systems. The co-pilot, who normally monitors the aircraft systems for the pilot, is also very busy trying to navigate - no simple task in the NOE environment. Sustained periods of NOE flight, even in clear weather during daylight, are extremely taxing to both crew members.

The information processing demands placed on the military helicopter pilot are carried to the extreme in the AH-64 (Advanced Attack Helicopter). In this aircraft the pilot is attempting to fly NOE, at night and/or in adverse weather, while viewing the outside world via a display generated by a Forward Looking InfraRed (FLIR) camera. This sensor scene is projected on a miniaturized cathode ray tube (CRT) mounted in front of the pilot's right eye. The CRT has symbolic aircraft systems and targeting information superimposed over the 40 degree field of view of the outside world. The pilot's information input in this scenario is severely restricted in terms of both the aircraft systems information, and in his view of the outside world. Adverse weather and enemy proximity exacerbate the problem and the possibility exists that the pilot's information processing capability can be overloaded. With current visual display technology alone, this type of operation - day/night, adverse weather, NOE flight becomes very demanding. The addition of multi-function displays and remote sensor viewing systems to our current helicopters may increase the visual and cognitive processing requirements on an already overloaded pilot.

Current Army requirements call for examining the feasibility of a single-pilot scout helicopter for the 1990's time frame. While a single-pilot aircraft eliminates crew-coordination problems and makes possible a smaller, lighter aircraft, the current heavy visual and motor workload may reach intolerable levels when shifted to one pilot.

The problem for the pilot is in receiving the correct systems information at a rate that enables him to make timely decisions to insure successful flight path management. The intensive visual demands on the pilot required by the tactics of NOE flight at night and in adverse weather and his need to monitor aircraft system indicators have suddenly and dramatically come into conflict. It is necessary, therefore, for cockpit designers to consider other than conventional visual technology for system information presentation.

APPLICATION OF SPEECH TECHNOLOGY IN THE COCKPIT

With the development of low cost, lightweight, reliable electronic voice display and control technology in the late 1970's there has been an impetus for human factors research to determine whether some of the traditional visual and motor human information transfer functions of low level or NOE helicopter flight and navigation can be transferred to the vocal and auditory channels. The military services have begun several programs to investigate voice technology. The Air Force has contracted for a research effort with General Dynamics to investigate the use of voice technology in the F-16, and the Navy has been funding a similar effort with Grumman for use in the F-14 as well as investigating the implementation of a voice system in the F-18. Concurrent with the Army's needs, NASA-Ames Research Center has recognized the need to investigate voice technology (both voice recognition and speech synthesis) for military and civilian helicopter operations which are now associated with high visual workload. These operations include, but are not limited to, search and rescue, off-shore drilling operations, forestry, crop dusting, and emergency medical evacuation. NASA-Langley Research Center has also recently embarked on a program investigation of voice input for general aviation aimed at the single pilot IFR mission.

Voice Command Input. Automatic Speech Recognition (ASR) is achieved by comparing incoming utterances with a set of previously stored templates (one for each word in the vocabulary); the computer then selects the closest match. The greater the similarity between the spoken word and one of the templates and the greater its dissimilarity from the other stored templates, the more likely it is that a correct match will be made. Most ASR technology available today is speaker dependent. This means that each user must form his or her set of templates by speaking each word that the device must recognize into a microphone which provides input to the ASR equipment. These reference templates are then stored for future use during recognition.

Most ASR devices currently being considered for airborne use are restricted to discrete utterances. Therefore, a user must pause between each word spoken for approximately 100 ms. to aid in the endpoint detection of each word. This means that the user can not speak conversationally to this type of ASR device.

There are also unique vocabulary size constraints inherent with each voice recognizer. First, there is a hardware limit to the number of words a device can recognize (usually between 100 and 200 words). Second, regardless of the hardware limitations, the larger the vocabulary, the more templates the machine has to chose from, thereby increasing the probability of misrecognitions. Use of syntax subsetting can potentially alleviate many of the vocabulary size problems.

The helicopter cockpit environment makes the accomplishment of accurate ASR more difficult because of the harsh operating environment. A variety of environmental factors such as noise, vibration and heat as well as psychological and physiological factors such as stress, fear, and fatigue impinge upon the successful recognition functioning of an ASR device. However, studies over the last several years in our laboratory in which ASR devices have been tested in simulated helicopter noise and vibration environments, as well as in flight with both fixed and rotary winged aircraft, have yielded encouragingly high recognition accuracy rates (Coler, 1982; Simpson, Coler, & Huff, 1982; Kersteen, 1982; Voorhees, Marchionda & Atchison, 1982, Coler, 1984). Tests recently concluded on connected word recognizers have also been encouraging (Coler, 1984).

Voice Output. Speech output technology falls essentially into two categories: synthesized (synthesis-by-rule) and digitized (synthesis-by-analysis) speech. Each of these techniques are discussed below.

Most commercially available speech synthesis devices employ synthesis-by-rule schemes using formant resonators. A formant resonator speech synthesizer models the human vocal tract and can reproduce the approximately 40 phonemes which comprise the English language. (Phonemes are the smallest units of speech that serve to distinguish one utterance or word from another in a given language). These phonemic units of speech are then concatenated into words, phrases and/or sentences according to a set of rules which take into account various linguistic and acoustic constraints,as well as predictable variations. Current speech synthesis technology tends to produce rather mechanical sounding speech. Listeners will often perceive a foreign accent in the speech produced by a synthesizer. In our laboratory, we have recently finished collecting data comparing different human accents with the "accent" of a speech synthesizer (Simpson, 1984). Preliminary analysis supports the contention that human listeners rate synthesized speech as being "accented" to the same degree and on the same dimensions as accented human speech.

Speech digitization (synthesis-by-analysis) is accomplished by converting analog speech signals into digital format and then storing it in computer memory. There is a trade-off involved with digitizing speech. The number of bits used to recreate the speech can be raised or lowered. Lowering the bit rate obviously takes up less memory but the quality of speech is also degraded. Raising the bit rate improves the quality of the speech to be nearly indistinguishable from analog recorded human speech, but at the cost of a large amount of memory. Therefore, the user must decide on an appropriate compromise for a particular application. Techniques such as Linear Predictive Coding (LPC) which is used by the U.S. Government for vocoders, can substantially lower the delivery bit rate while maintaining a high level of "humanness" of the speech.

For the potential use in a helicopter cockpit, synthesized speech may be more versatile than digitized speech. First, by virtue of the fact that synthesized speech sounds mechanical it functions effectively as a voice warning system since it stands out against the background radio communications ongoing in the cockpit. Simpson (1982) reports that a high fidelity representation of human speech enunciating a warning message might very easily blend with other communications, whereas a more mechanical sounding speech will stand out. This perceptual salience of synthesized speech was also reported subjectively, by the helicopter pilots that served as subjects in a recent study (Voorhees, Bucher, Huff, Simpson, and Williams 1983).

Another characteristic which could make a phoneme based synthetic speech system more versatile is that vocabulary size does not affect memory size requirements. Whereas digitized speech systems require each individual word to be stored in memory, synthetic speech systems have a virtually unlimited vocabulary since only the 40 individual phomemes are stored. In effect, digitized speech provides a high fidelity speech output similar to tape recording, but with a tape recorder's limitations, in that for any message to be spoken the words that comprise it must be stored in memory. While synthesized speech might offer a more versatile speech output because it is capable of delivering any message vocabulary with only software input it may not have the sound quality of a human speaker as does the digitized speech system.

The type of speech system which is optimal for cockpit applications depends not only on the type of information output desired, but also on the other ongoing cognitive, perceptual, and motor demands on the pilot. When a pilot receives information via a voice message, several steps are involved between the reception of the physical waveform that is the speech message and the pilot's comprehension of the message (Simpson, 1983). First, he must notice that someone or something is speaking to him; this is the detection step. Next he must direct his attention to the speech - the selective attention step. Then he must correctly perceive the speech sounds that make up the words of the message; this is the copy step in the sense of "copying" an ATC clearance. At this stage the pilot, if asked, could recite the message. Note that he does not necessarily have to know what the message as a whole means to do this. When the pilot extracts a meaning from the message - the comprehension step - he then can be said to have understood the message. Finally, in order to use the information conveyed by the message at a later time, the pilot must have stored and be able to retrieve the information content of the message. Proposed applications of different electronic voice output systems for use in aircraft cockpits must be evaluated in terms of their capability to enhance these different steps in message processing. Deciding what voice output system to use based on the "humanness" quality of its speech output is the wrong approach to solving the cockpit information output problem.

It should be emphasized that the addition of voice output in the cockpit should not intended to replace the visual display of information. Rather it should be used to help reduce the extreme visual workload of current helicopter missions by alerting pilots to time critical items as well as providing necessary flight information upon request. However, pilots must still be able to scan their instruments for an overall status check of conditions. The goal of any cockpit information system, regardless of its organization or specific components, is to provide the pilot with the maximum amount of information transfer under conditions of minimum cognitive effort. Flight under difficult or threatening conditions will always be extremely demanding of human resources. The more efficient the communication of information to the pilot, the more resources he will have for executing his primary task of flight path management and for coping with emergency events when they arise. Definitive data are needed on the optimum visual display design which can be integrated with voice display of information to reduce the information processing demands of current and future rotorcraft operations.

INTEGRATION OF INFORMATION DISPLAYS IN THE COCKPIT

The availability of the new voice and visual display technology for helicopter cockpit designers could create some of the same problems of how to apply these systems as have other recent technological advances such as CRTs and multi-function displays. The temptation can exist for the designer to use advances in technology in a wide variety of applications just because they are new and available. This can lead to a situation in which parts of a display system function well when evaluated by themselves in a laboratory or a simulator but are not efficient when used as parts of an integrated information system within a flight mission context. Multi-function keys associated with a CRT are a very efficient way of providing access to a large amount of information while using only a limited amount of panel space - but their usefulness to a pilot flying NOE with both hands working controls while looking outside the cockpit is questionable.

A similar situation could occur with voice technology. Incorporating talking altimeters, talking radar warning devices, talking fuel gauges, talking caution/warning panels, etc., will turn the cockpit into a bedlam of auditory messages. On the input side, installing voice controlled radio tuners, voice controlled navigation aids, voice controlled target acquisition systems, etc , in the cockpit will result in the pilot's having to train several different types of recognition equipment each with its own vocabulary.

One solution to this possibility for misapplication of new technology is a single voice recognition and speech delivery system, integrated with the visual display and manual input systems. Optimizing and implementing visual displays and voice input/output systems independently may not solve the problems of cognitive and perceptual overload currently experienced by the helicopter pilot. Careless application of these new technologies may result in an increase in pilot workload. Only by careful integration of these multi-modal information systems can information overload be reduced. All cockpit informational subsystems should be interfaced to a single system and a reasonable priority logic designed. The voice system must become a part of an integrated cockpit where visual output, voice output, manual input, and voice command input operate together coherently (Voorhees & Kersteen, 1983).

There are specific characteristics associated with visual and voice output displays that must be considered when integrating these multimodal systems. Visual displays present information almost instantaneously, and have a very fast update rate. Information presented visually can convey a great deal of information with a relatively simple presentation - as with a symbol. The use, however, of some presentation formats such as long strings of text on a CRT can require long scan and processing times. Also, if the pilot is not visually monitoring the display (a task which takes his attention away from the flight task), information can come and go unnoticed by the pilot. The presentation of visual information can be very unobtrusive and therefore non-distracting but this means that information may be present for some time before it is noticed.

Speech displays, on the other hand, are very attention demanding and therefore they can be obtrusive. While this obtrusiveness of speech displays means that a pilot will almost surely detect that there has been output there is the possibility that an ongoing higher priority task will be interrupted. While speech output of information that is normally presented visually can reduce visual processing loads, there could be an increase in the already high auditory processing demands. Speech messages, because of their sequential nature, are very dependent on the listener hearing <u>every</u> part of the message if it is to be correctly understood. However, because speech is a well learned cognitive code, a great deal of sophiscated encoding can be done with a relatively short message. Finally, speech displays while they can only be processed one at a time, have the advantage of being omnidirectional - that is message reception is not dependent on the orientation of the pilot's head.

When correctly integrated, speech and visual cockpit displays could provide a dual output system in which speech output would focus immediate attention on the highest priority information and the visual output would serve as continuous backup for a quick scan of the total situation. Integrated displays, however, unless they are carefully designed can exacerbate processing constraints present in either visual and speech displays alone. Two of the most apparent problems with integrated displays are: display priority and temporal veridicality.

1. <u>Display Priority</u>. Visual displays, if properly designed, can display more than one item of information simultaneously; speech displays can only present one item of information at a time. Most visual displays, however, do not attempt to order information by importance; this task is left to the pilot. Speech displays <u>must</u> output information by priority if they are to be effective. This system priority logic, if done properly, can offload the decision making task from the pilot, thus saving him time. But this increased level of sophistication from the display system requires higher levels of "intelligence" on the part of the system.

2. <u>Temporal Veridicality</u>. Ideally a display system should never confuse the pilot. It must always give him the most up-to-date

information possible. Visual displays, because of their almost instantaneous nature, can change rapidly enough to give time veridical information. Speech systems, because of the time required to articulate a message, may lag behind actual events, particularly if the messages are stored and delivered as strings of words. This creates a difficulty with integrated displays because the visual and speech displays may be giving conflicting information. The temporal inconsistency could cause a pilot to lose confidence in an integrated display system (Simpson, 1983).

We have been investigating the integration problem in a series of full mission simulations. The first of these was the Speech Command Auditory Display System (SCADS) experiment. The next was the Voice Interactive Electronic Warning System (VIEWS) project which was done in response to a request by the Army Aircraft Survivability Program Manager. These studies have been presented elsewhere and are briefly described below. A third mission simulation in which voice and visual display systems are investigated is being developed and will be carried out at the completion of a series of part-task experiments.

Speech Command Auditory Display System (SCADS)

Building on much of the voice input/output and visual displays work done within our laboratory, the Speech Command Auditory Display system (SCADS) mission integration simulation was conducted (Voorhees et. al., 1982). This study compared the use of voice recognition and speech synthesis with visual displays in a helicopter simulation. Fourteen non-pilot subjects were tested on a computer graphic task simulation of NOE flight using three different types of instrument display formats. Subjects were tested in ten sessions (one per week) maneuvering a helicopter symbol through a maze of obstacles displayed on a picture system graphics screen. This maze task (Simulated Helicopter Abstract Mission Simulation - SHAMSIM) was developed to provide subjects with a functional representation of NOE flight (Huff and Voorhees, 1984). Information on airspeed, altitude, and torque (power setting) was necessary for optimum performance on the task. These flight parameters were presented by either conventional dial gauges (control group), a head-up display (HUD) located on the graphics screen around the maze, or a voice command-speech synthesis system. All subjects received training for four weeks using the conventional dial gauges. Matched groups were then formed and tested for three weeks. At the end of the seventh week, the ten subjects were again given the conventional dials and, along with the four subjects in the control group, tested for an additional three sessions. Analysis of the performance showed a significant difference on the seventh week performance, with the HUD and the speech group performing better than the control group, and the speech group performing better than the HUD group.

This study allowed us to confirm some of our hypotheses on how to use speech input/output systems effectively in helicopter cockpits. The subject's attention shift while using the conventional dials did not result in significantly more obstacle hits, rather it was manifest in slower speeds through the maze. This finding corralated with reports of how helicopter pilots tend to respond to visual overloading in the actual flight environment. The helicopter pilot, when confronted with the visual overload of NOE flight, slows down in an attempt to minimize the visual conflict, with the priority of obstacle avoidance. The subjects who were using the speech output system reported difficulty in determining rate information. The voice system could only respond with the exact unitary reading at the time it was queried, i.e. "20 knots". What the subjects seemed to want was predictive rate information on acceleration or deceleration so they repeatedly requested a parameter - i.e. "Airspeed" - "20 knots", "Airspeed" -"18 knots", "Airspeed" - "17 knots". This confirmed our assertion that voice output cannot be effectively used as a one-to-one replacement for analog visual information (Voorhees, Marchondia, & Acthinson, 1982).

Voice Interactive Electronic Warning System (VIEWS)

This second of a series of cockpit integration studies conducted within our laboratory was designed to examine the use of an integrated visual and speech display for a threat warning system. The study was conducted with seven military helicopter pilots performing the SHAMSIM-based functional NOE flying task. Added to the SHAMSIM task was a secondary task of trying to avoid enemy radar-guided gun and missile systems. This research project (Voorhees, et.al., 1983) was an initial attempt to solve the display priority and temporal veridicality problems of an integrated system. Pilots were given one day of training with the visual symbols and speech messages to be displayed by the experimental Radar Warning Receiver (RWR). After RWR training all subjects received training with flying the SHASMSIM task without threats present. On the second day the pilots were required to fly the task with a "low" level of threats. The level of threats increased each day during the week of testing as one independent variable. Voice type was manipulated as the second independent variable: female, male, and phoneme synthesized speech were digitized using a Texas Instruments (TI) Portable Analysis-Synthesis System (PASS) and delivered to the pilots with a TI Speech Education Module (SEM) system. (This hardware was used to replicate the experimental system being evaluated for the Army.) A fourth voice condition - no voice - was used to counterbalance the design. On the third and fourth days of testing various failure modes were introduced during the experimental runs: voice system failure, visual system failure, and total system failure.

The development of a complex output priority logic largely eliminated the problems of temporal veridicality and display priority. In brief, this logic eliminated all message queueing and updated each word of the three word message just prior to it being spoken. This logic also implemented a message update feature called a "coda" at the end of a message that had been spoken while the real time situation was changing. This coda eliminated the need to repeat a whole message to give an up-to-date output. A special symbol was developed ("message being spoken" pointer) which was displayed on the visual display screen directly under the visual symbol that the speech message was addressing. Thus the pilot always knew which visual symbol the speech display was talking about. This pointer helped in reducing uncertainties concerning the temporal verdicality of the integrated display.

It was also determined that while pilots could use either the visual or speech systems individually for successful avoidance of radar guided threats, they prefered to have both systems working together. Some individual differences were noted in the pilot's preference of visual or speech information output, and our laboratory is currently exploring this phenomena to see if there is a possible link between this preference and spatial vs verbal learning preferences (Voorhees, et al, 1983).

FUTURE RESEARCH

Early in our research program investigating integration of displays we identified three major areas of information transfer that had the highest priority for integrated voice/visual/motor cockpit information systems. These three categories of information are essential for pilot survival, and therefore should have priority for multi-modal information display integration.

1. Aircraft internal status information - fuel, operation limits (temperatures and pressures), and warning and caution information.

2. Immediate external flight environment - wires, ground obstacles, or other aircraft.

3. Threat situation - detection by enemy radar, laser, or optical tracking equipment.

The first category - status information - was investigated at a very basic level in the SCADS experiment. The category of enemy threats, while uniquely a military problem, has been dealt with extensively on the VIEWS project. Work continues on several part task studies examining features such as warning message length, alerting prefixes, incorporating speech output to supplement the tones, and the most appropriate visual output: symbols, words, acronyms, or icons. The next full scale integration experiment currently being planned will examine these three areas of critical information transfer in further detail within a single simulation framework.

CONCLUDING REMARKS

Voice input/output technology can be a viable adjunct to visual display output and motor input. However, the current visual and motor information systems in the cockpit need to be improved. Also, merely adding voice technology to existing displays, or trying to replace visual/motor displays with voice technology on a one-to-one basis can create problems for the pilot. The difficulty is that the fundamental questions of how a pilot should interact with his information systems have not been answered for the new mission requirements that we have placed on the pilot. We should address the questions of what information is necessary, and when it is necessary, before we begin designing how to deliver the information. There will be continuing interest from design engineers to implement technology as soon as it is electronically feasible, but unless the fundamental questions are answered, and the integration issues are addressed, the result can be information display systems that will not be useful to the pilot or will add to his workload.

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BIOGRAPHIES

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ANNEX R-XII

THEORY AND MEASUREMENT OF HUMAN WORKLOAD

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Annex R-XII to Appendix R

THEORY AND MEASUREMENT OF HUMAN WORKLOAD

R-XII-1. The report, "Theory and Measurement of Human Workload" is reproduced on the following pages. The report was prepared by Sandra G. Hart of the NASA-Ames Research Center, Moffett Field, CA.

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THEORY AND MEASUREMENT OF HUMAN WORKLOAD

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INTRODUCTION

Performing any task has a "cost" that can be conceptualized in terms of resources consumed, inability to perform alternative activities, or operator workload. The cost to system hardware of performing its part in a man-machine system can be operationally defined and measured objectively. For example, computer memory or fuel consumed, mechanical strain, or rate of throughput reflect the load placed on a machine. Although other variables such as environment or maintenance might affect this value, their influence can be predicted and quantified. Furthermore, machines cannot perceive the task requirements any other way than literally; individual biases or strategies are not possible, and every response is overt, predetermined by the system architecture.

This is not the case for measuring the cost of task performance to a human operator, however. Operator workload has been the topic of research and debate for decades. Although the term has intuitive meaning for most, a precise definition has eluded both scientific and engineering communities. Candidate definitions and models may be distinguished by where they locate the source of workload in a man-machine system, which variables are included, and the measurement tools recommended. There is equally little agreement about how workload might be measured and why one would want to do so. The goals of workload research efforts range from developing or testing techniques and theories, to assessing workload in an existing system, predicting it in an proposed system, or modifying unacceptable levels. Although, it is assumed workload is a measurable entity, accumulated information resembles the proverbial descriptions of an elephant provided by blind men touching its body, tail and trunk; each description is correct (given the restricted information available to each evaluator and information-gathering constraints imposed by their blindness), yet none suffices to fully describe the animal nor to predict how it might function.

This chapter describes what is known about the locus of human workload, how it might be measured, what influences it, and why it is of theoretical and practical concern. Typical definitions and motives for measuring and predicting workload are reviewed to illustrate the wide range of phenomena that have been considered relevant. A theoretical structure is proposed that relates and integrates factors within tasks, operators, and environments that create or influence workload. Three different, but related, attributes of workload are distinguished and described in some detail: the demands imposed on a man-machine system, its response to them, and the subjective experiences of operators. Next, five classes of procedures that have been used to predict and measure workload are described and evaluated: (1) subjective ratings, (2) primary task performance, (3) secondary task performance, (4) physiological recordings, and (5) analytic procedures. The selection and application of appropriate tools to predicting or assessing imposed workload, system performance, or the behavior and experiences of operators are reviewed in a final section.

WHY MEASURE WORKLOAD?

Setting aside the problem of definition, for the moment, it is appropriate to discuss why there is a continuing theoretical and practical interest in a something as ephemeral as "workload". Even though a precise and parsimonious definition has proven elusive, most people have the intuitive feeling that such a phenomenon exists, and that it is an important limitation to both system performance and operator acceptance (Johanssen, et al, 1979). There are three major motives for workload analysis: (1) Prediction of workload for systems or procedures that do not yet exist; (2) Assessment of workload in existing systems; and (3) Modification of unacceptable levels of workload. The three are related, obviously, and reflect many of the same underlying principles. Yet, measurement techniques that are valid and practical for one may not be for another and different questions and problems require different procedures. For example, techniques appropriate for predicting workload necessarily focus on imposed workload and are most effectively applied early in development, before a design is finalized or placed into production. Assessment, on the other hand, is conducted on existing or simulated systems, and is accomplished by measuring system responses and operator experiences. Modification may involve identification of a workload problem (by observation, empirical testing, or prediction), predicting the effects of one or more solutions, implementing one, and then evaluating the results empirically. This may require a combination of different techniques and levels of analysis.

System Performance

Practical questions about whether operators can handle the demands placed on them under normal and abnormal circumstances provide the primary motivation for workload analyses in operational environments. As the hardware and software of advanced systems have become increasingly reliable, the capabilities of the operators have not changed. Thus, the performance and reliability of the system as a whole is limited by the behavior and reliability of human operators. There is no simple relationship between workload and performance, however, even though the typical motive for measuring workload is to predict performance. Then, why not measure performance directly, especially since it can be measured relatively more easily than workload? The answer is that a high level of performance can be maintained as task demands and mental workload gradually increase - - right up to the point where operators' abilities are exceeded (or they lower their performance standard) and performance deteriorates. Thus, the workload "reserve" of an operator under one set of circumstances might predict what would happen if task demands were increased still further, serving as a better predictor of future performance than measures of current performance.

Design tradeoffs

It is particularly difficult to predict the workload and performance of systems that do not yet exist or for tasks that will be performed in novel environments. Such predictions are required during the normal design process to insure that the projected crew complement will be able to accomplish mission requirements long before operational systems exist for empirical testing. Crew workload must not only be acceptable on the average, but this must be true for each crewmember individually throughout the time on duty, as well. Evaluating the workload imposed by different equipment, procedures, requirements, or environments, allows designers to make intelligent choices among control or display design alternatives. By refering to existing systems and extrapolating from models of human behavior, some sources of loading likely to cause operational problems can be identified and solutions posed. For example, scheduling changes may solve some problems, whereas modifying the format, source, or complexity of information or the locus of control (man or machine) may solve others.

A man-machine system might be regarded as an organism with sensors, effectors, and intelligence having resources that can be dynamically and optimally employed without distinction among living, mechanical, or electronic components. The most capable or least loaded resource (human or machine) should assume responsibility for specific tasks depending on the reserve capacities of all available system components. If the momentary workload of one operator is sufficiently great, another resource might be directed to unburden him (by engaging an automatic system, involving an additional operator, or providing different information). In order for such an adaptive system to be realized, it requires flexibility in system design and the ability to measure "instantaneous" operator workload in the operational setting.

Certification for Operational Readiness

For systems that transport the public, such as aircraft, certification by a third party such as a government agency is required. This agency reviews engineering data provided by manufacturers about hardware and procedures and monitors part-task and full-mission testing to determine whether the vehicle can be operated safely with acceptable levels of operator workload. In a recent controversy over the certification of several commercial aircraft to operate with two-man crews, the desire of manufacturers and airlines to reduce operational costs conflicted with labor considerations and raised concerns over safety. A Presidental Task Force was convened to review the evidence (McLucas, Drinkwater, & Leaf, 1981). Although safety records demonstrated that two crewmembers can operate as safely as three (suggesting that automation has reduced crew workload enough to eliminate the need for a third crewmember), a third crewmember might provide an extra margin of safety, relieving other crewmembers during periods of high workload or when unexpected events occur. Much of the debate focused on how pilot workload, particularly mental workload, might be assessed. It became clear that the ambiguity of definition and lack of standardized objective measures constituted a practical problem in answering questions and resolving the conflicts that arose.

Operator variables

Another motivation for measuring workload concerns the goals and job satisfaction of individual operators. Humans have interests beyond optimization of traditional indices of system performance (Rouse, 1979). Thus, their physical, emotional, and mental state and willingness to perform assigned activities (compared to their ability to do so) are relevant concerns. Workload and job satisfaction may not be directly related. For example, few pilots might wish to return to a fully manual flight mode, but most would prefer to retain some physical and mental involvement in controlling an aircraft. Exercising skills and performing difficult tasks may lead to personal satisfaction, while passively monitoring the system might cause stress and dissatisfaction. Operator-related variables may be reflected in economic decisions (e. g., aircraft certification and aircrew contract negotiations), the long-term health of operators, acceptable working schedules, and criterion for selecting operators.

Training considerations

Ordinary experiences suggest that task demands and required effort seem to decrease with practice. Furthermore, a change in how tasks are performed may occur as proficiency increases, so operator workload may change qualitatively as well as quantitatively. It appears that skill level, developing "automatic" behaviors, coordinating previously unrelated activities, and the level of workload experienced are related. Establishing objective evidence for and measurement of this is necessary to design training programs for new or existing systems or transitioning from one version of a system to another. Training requirements are an important consideration in advance of operational testing of a new system, as well. For example, training may be more difficult for highly automated systems because operators must learn two modes of operation - - the nominal, automated mode as well as the manual backup mode. For some tasks, the cost of the training required to achieve acceptable levels of performance and workload might be prohibitive for a proposed configuration. Alternative solutions, such as computer aiding, additional crew members, or revised hardware or procedures might be considered early in the design process in such cases rather than waiting until the system is operational.

THEORIES AND DEFINITIONS

Just as there are many motives for evaluating or predicting workload, there are many theories about and conceptualizations of the construct. To many system designers and engineers, workload is defined by the task demands - - literally the "work" that is "loaded" on an operator. Task demands may be characterized by the frequency and amplitude of control tasks, the number of discrete signals or responses, or the time required for individual functions. Task difficulty is not always obvious, however, due to subjective and person-specific phenomena. Furthermore, it is often inferred from performance measures that may only reflect variations in effort and skill level. The temporal component has been emphasized by equating workload with "time pressure" (i. e., required versus available time). This formulation is the explicit basis of task analysis and computer models of human operators and the implicit foundation for other approaches. It focuses on a priori requirements rather than the behavior and experiences of operators. Task demands are evaluated empirically by measures of performance and operator opinion and predicted by manipulating the values of constants in system models.

In operational environments, the focus is on performance; as long as adequate performance is maintained, workload is of little concern. Deteriorating performance, however, suggests that the workload has exceeded an operator's capacity. The level of accomplishment relative to system goals is emphasized. As with approaches that focus on task requirements, performance-based analyses are limited because operators may adopt different strategies or increase their effort to maintain a constant level of performance in the face of increased task demands. No measurable change in performance may occur until a critical level of loading is reached. Thus, measures of performance are not predictive of what might happen under a different set of circumstances.

Others conceive of workload in terms of physiological consequences, focusing on arousal and stress. They measure physiological changes in heart rate, blood pressure, respiration, galvanic skin response, muscle tension, and pupil size. Although these measures reflect an operator's physiological activation, they are each sensitive to influences other than task demands, performance, or effort, and have limited application in predicting workload during the design phases. In addition, they may not be sensitive to some types of task demands or reflect the same task variables that influence specific operators' subjective experiences.

In the tradition of ergonomics, workload has been conceptualized as effort, particularly physical effort, expended to meet task demands. The focus is on behavior rather than requirements or accomplishments. An operator's output is evaluated absolutely or in relation to his or her supposed capacity. Physical efforts measured by continuous control activity, the rate and freqeueny of discrete responses, the intensity of muscular movement and changes in heart rate and respiration associated with exercise have been equated with the workloads of many activities. One difficulty in relating physical output to workload is that many repetitive, overlearned behaviors may be performed with no conscious perception of effort on the part of the operator (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) or distruptive influence on other. concurrent tasks (Wickens & Derrick, 1981). The primary advantage of this conceptualization may be the availability of "objective" measures and the possiblity of operational definitions of terms.

More recently, workload definitions have emphasized cognition and attention, focusing on mental effort rather than physical. This shift in focus accompanied the introduction of automation into systems previously characterized by direct physical control. The structural properties and capacities of information processing mechanisms that intervene between the task requirements and operators' responses have been studied extensively. Workload has been defined as the degree to which tasks compete for common processing mechanisms or structures and the capacity remaining to perform additional tasks.

In early models of human information processing, a discrete number of information "channels" were postulated with bottlenecks or filters hypothesized at different points between the incoming information and the observed behavior (Broadbent, 1958; Moray, 1967; Treisman, 1969). Within this framework, performance was evaluated by the amount of information correctly processed from the attended channel. Task difficulty was equated with the amount or rate of information a subject was required to process. Information was expressed in dimensionless binary units (Bits), each representing a reduction in uncertainty by one half. Workload was defined as competition for limited attention mechanisms or the cost of switching from one focus of attention to another. In later structural models, serial or parallel stages of processing rather than information channels, were postulated (Kantowitz & Knight, 1976 a; b; Sanders, 1979; Sternberg, 1969; 1975). It was assumed that each process could be devoted to only one activity at a time, with task elements competing for access to limited structures. Performance was evaluated by measuring the time required to complete different tasks and task elements. An increase in response time was interpreted as evidence for additional processing stages or competition for a single stage.

With resource or capacity models, the degree to which different tasks could share limited resources was emphasized. Tasks were assumed to demand resources from a single undifferentiated pool (Kahneman, 1973) or from multiple, structure- specific pools (Navon & Gopher, 1979; Wickens & Kessel, 1979) with limited capacity. Since different tasks require different amounts of capacity, a hypothetical quantity termed "spare capacity" was postulated for tasks that required less than an operator's full capacity. It was assumed that resources could be allocated (up to their limit) in graded quantities among separate activities. Evidence for an undifferentiated pool of resources came from the observation that tasks that appeared to have little in common still interfered with each other's performance (Kahneman, 1973). In fact, it was suggested that an individual's capacity to perform work could vary as a function of arousal or motivation (Kahneman, 1973). The more common observation that some tasks interfered with each other more than others provided evidence for a multiple resource model. It was postulated that different amounts and types of resources are required for different tasks (Navon & Gopher, 1979; Norman & Bobrow, 1975). Performance limitations arise from insufficient resources in one or more processes that might be differentiated by the modality of input or output, stages of processing, or code of central processing (Wickens & Kessel, 1979). Thus, different tasks generate patterns of mental load with respect to different resources. This suggests that multiple measures are required to assess the loading on different capacities (Shingledecker, Crabtree, & Acton, 1982). The secondary-task paradigm, in which an additional task is superimposed on a primary task, has been employed extensively to address the question of how resources are constrained and allocated. Secondary task performance is evaluated to estimate reserve capacity available after primary task performance (Bahrick, Noble, & Fitts, 1954; Ogden, Levine, & Eisner, 1979). Although the focus is on performance, operators' successes or failures in satisfying task demands are used to infer the underlying processes.

Human minds are never empty or idle. An operator occupied by the most tedious and boring job may have thoughts filled with complex and detailed daydreams, intricate plans, or philosophical musings - - a spontaneous (and relatively invisible) secondary task. Alternatively, reserve mental capacity might be used for continuous monitoring of the surroundings. As the effort required to perform a task is increased, attention may be withdrawn from other activities to be concentrated on it (Kahneman, 1973). Thus, it might be more parsimonious to characterize a tasks' demands by the degree to which an operator's mental facilities are "captured" and devoted to achieving task goals.

Parsimony in defining and modeling mental workload has fallen prey to the same realities that have complicated other attempts to model the human mind. "Bits" of information have become "chunks", single channel concepts have evolved into multiple channel concepts, single bottlenecks in the flow of information through the system have become filters or multiple bottlenecks, single serial pathways have become many serial and parallel stages, and single reservoirs of resources have become multiple reservoirs in order to explain behavior in the simplest of experimental tasks. This may be distressing, experimentally and theoretically, yet it is just this amazing capacity and flexibility that requires human operators to remain firmly "in-the-loop" in virtually all complex systems. Given experience, appropriate information, and task structuring, exceptionally complex and objectively loading tasks can be performed successfully with apparently acceptable levels of workload.

The concepts of information processing channels, attention, capacity, processing stages, and pools of resources are all metaphors for internal structures. They are invoked to explain why available information is not processed, stored. nor acted upon and why task requirements are not met. Unfortunately, there is no agreement about what are the underlying structures. Nevertheless, concepts derived from models of human information processing have intuitive appeal in the analysis of workload. They provide an organizational structure for empirical data and allow theory-based predictions about whether subtask combinations will compete for limited physical or mental resources.

Thus, it is possible that many apparently unrelated variables might be relevant in predicting, measuring, and experiencing workload and that motivations for invoking the concept vary widely. Because of the different uses of the term and the wealth of contributing factors, a conceptual framework will be outlined so that different sources, modifiers, and indictors of workload can be described and related. The term "imposed workload" will be used to refer to the situation encountered by an operator. It is created by task objectives and structure, the environment, and incidental events occuring during a given task performance. The term "system response" will be used to refer to the actual performance of a task. It is motivated and guided by the imposed demands, but it reflects the perceptions of specific operators about task requirements, the strategies, effort, and systems resources used to accomplish these requirements, and the physical, sensory, and cognitive skills of the operators. Information about system status and control inputs inform operators whether they have selected the correct strategy or are exerting sufficient effort, allowing them to secondary-task paradigm, in which an additional task is superimposed on a primary task, has been employed extensively to address the question of how resources are constrained and allocated. Secondary task performance is evaluated to estimate reserve capacity available after primary task performance (Bahrick, Noble, & Fitts, 1954; Ogden, Levine, & Eisner, 1979). Although the focus is on performance, operators' successes or failures in satisfying task demands are used to infer the underlying processes.

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Imposed Workload

Task Objectives

In general, human behavior is goal directed; actions are performed and information processed to accomplish an objective. Goals may be general, leaving operators free to select among strategies, actions, and solutions or impose specific constraints. Requirements for speed, accuracy, efficiency, creativity, or reliability may be defined by target values, upper or lower limits, or an acceptable range. Task objectives influence the level and type of effort and the priority assigned to task elements. An objectively easy task can be made difficult by requiring greater speed or accuracy, or a difficult task may impose little workload if any level is acceptable.

Environmental Variables

The operational environment in which a task is performed contributes to its difficulty. The physical environment is created by the location (e.g. undersea, very low or high altitudes, space), climate (e. g. temperature, humidity), workstation layout, noise and lighting levels, and threat from natural or man-made sources. The social environment is created by interactions among physically present members of a crew or with others via voice, video, or computer link. The environment's impact may be indirect or direct and some tasks may be impossible to perform in some environments no matter how much effort is exerted. If operators modify their strategies, performance criteria, or experience different levels of stress, a task performed in a non-judgemental environment with no ego- or life-threatening consequences of poor performance may impose different load than the same task performed in a more threatening environment. Tasks performed where life support systems are necessary impose additional requirements including the need to control and maintain the environment (Johnson, Bershader, & Leifer, 1983). Although machines are responsible for monitoring and maintaining life-support systems, they require an operator's attention only if they malfunction, much as the autonomic nervous system maintains homeostasis without conscious attention or control. The absolute requirement that such systems function reliably, however, makes them a continuing concern for the human crew and contributes, albeit subtly, to workload. Clothing designed to protect operators from hostile environments, although necessary, may further increase the difficulty and discomfort of working in life-threatening environments.

Task Structure

Temporal organization. The organization and structure of a task is reflected in its duration, the rate and order in which task elements must be performed, and the degree to which they can be deferred. For some activities, formal procedures may govern every aspect, for others the timing and sequencing are left to the operator's discretion. Some subtasks must be done immediately because they are so important or because they will become difficult or impossible to do if delayed. Others can be deferred for several minutes with no performance decrement, but they must be done within a time window. Planning and preparing for future events are required for safe operation, but are not time critical; they can be deferred if higher-priority tasks intervene.

System designers assume there is a minimum time required to accomplish component tasks and to switch between task elements. They define the time pressure associated with task performance as the ratio between the time required to perform a task and the time available (Sheridan & Stassen, 1979). As this value nears unity, workload is assumed to increase. Because workload is determined by the pacing of events as well as their complexity, the term time pressure has been used interchangeably with workload (Eggemeier, et al, 1982; Parks, 1979; Sheridan & Simpson, 1979). However, time pressure is as ill-defined a term as workload. Task duration by itself has no necessary relationship with workload; it is easy to imagine brief activities that impose extreme load or very long ones that impose little load. In addition, the number of different tasks performed within an interval may or may not relate to workload either, depending on subtask characteristics and individual demands. Some tasks may be performed concurrently within the same interval of time, whereas others may have to be performed sequentially. In either case, the intensity of effort exerted per unit of time, averaged across the task duration, is more likely to influence workload than the intervals between successive tasks. Rather than being an objective quantity, time pressure resides in the eye of the beholder. Individual differences lead some to seek external time pressure to get started on a task or to relieve boredom, whereas others cannot function under it.

System Resources. The resources available in modern systems include information, hardware (including computers), software, other crew members and support personnel. Workload and system performance rely on the availability and reliability of these resources and an operator's effective management and use of them. Information displays provide data for computations, decisions, predictions, and control inputs. They may inform operators that the system state is unchanged, functioning normally, or malfunctioning. The effect of information displays on workload may depend more on its timeliness and format than on the absolute amount available. For example, a delayed landing clearance may decrease workload by resolving uncertainty even if its reception requires considerable processing. Operationally relevant information obtained each time an operator samples an instrument panel or communications channel is considerably less than the total information available. Not only is the information absorbed in related "chunks", but changes and deviations are perceived and processed while status quo assurances are noted at the most trivial level. For example, the synchronized positioning of dozens of indicators on dials forms a well-learned pattern if all systems are in a nominal state. Operators perceive this pattern in a quick scan, rather than reading the numerical values indicated by the position of each indicator.

If displays present summary information about mission segments and integrate relevant system elements, operators need perform only a single task at any time - - initiating well-learned or automated sequences of events or recognizing the completion of one. If the performance characteristics of controls and displays fit operators' mental models of the system, then available resources will be used more efficiently. If they do not, then they must perform additional mental operations to translate back and forth between displays of actions and their own cognitive representations of them (National Research Council, 1982), thereby increasing workload and decreasing system efficiency.

Operator qualifications

Systems are designed to accommodate most potential operators, and, when procedures and training programs are established, it is with their capabilities and previous experience in mind. Designing a system to allow any operator to manage it with minimal workload is rarely cost-effective (in terms of additional hardware, training, crewmembers, or automation) and may be impossible. Instead, the user-population is restricted to individuals who meet certain minimum qualifications. The selection criteria may be based on formal education, physical capabilities, past experience, sex, age, or personality traits, etc. In research settings, operators may be specialists who are part of the design team, potential users of the system, or a random sample of the population in general. Because the completed system will be managed by an "average" operator, it is important that the skills, judgements, and goals of these individuals are considered rather than relying completely on the preferences of uniquely skilled specialists such as test pilots.

The training requirements and selection criteria for operators may change during the transition from direct, operator-controlled systems to predominantly automatic systems. The qualitites associated with success in one may not be appropriate for the other and additional training many not provide an adequate solution. If operators cannot be trained to control an advanced system adequately, then information displays and system interfaces might have to be simplified to allow new or existing operators to meet minimum performance criteria.

Incidental Variables

The issues raised in the preceeding section suggest intended or potential load factors imposed on human operators. If a situation is carefully controlled, the workload that is actually imposed during a given task performance should be similar to the intended level. If not, the task (or the operator's perception of it), might be modified by unexpected changes in the environment, errors made by the operator, or hardware malfunctions. These may have a momentary effect on workload or influence the remainder of the task by altering its structure or organization (Hart & Bortolussi, 1983). Unexpected situations can increase workload even if no corrective action is taken and considerable additional effort may be required to provide a remedy. If an error disrupts a practiced sequence of behaviors, completing the remaining task elements out of sequence or with conscious attention to details that are normally accomplished automatically may increase workload substantially, even if no corrective actions are taken. Thus, incidental variables may modify a task so that the workload imposed is very different from one time the task is performed to the next or they may contribute minor variations or "noise" to the levels of load for different operators. Their occurrence can be anticipated and computed, however, to determine the envelope within which the task could be performed and to allow a post hoc reevaluation of the actual workload level.

System Response

Operators generally strive to achieve their perception of the task requirements. They compare current performance to previously established standards, adopt more efficient strategies, and modify their behavior to improve or maintain performance. Because an operator's understanding of what he or she is expected to do forms the basis for actions and experiences, this factor may play an important role in the level of workload experienced.

Operator Strategies

Many tasks require particular strategies if good performance is to be achieved with acceptable workload. For complex tasks, however, alternative behavior patterns may result in acceptable performance, even though not all of the alternatives are obvious to an operator or the system designer. As operators become familiar with a job, they develop hypotheses about the structure, evolve strategies to adjust the level of workload, and adopt personal criteria in addition to (or in place of) those of the task originator (Johannsen, et al, 1979). Strategy selection may depend on operators' general experiences, specific task and system understanding, a desire to capitalize on skills and strengths, or willingness to take risks. In addition, different individuals may be predisposed to elect one strategy rather than another resulting in differences in workload and performance (Damos, 1984). The operator's strategies then determine the system resources used, level and type of effort exerted, interim system performance goals, and information considered.

Operator Behavior

Operators exert effort in a variety of ways. Physical effort is the easiest to conceptualize, observe, and measure, yet its importance in advanced systems is diminishing. Mental effort is inferred from the structure and requirements of a task, changes in performance and physiological functions, and subjective reports. Even though it serves as a potent intervening variable between measurable stimuli and measurable responses, it is difficult to quantify directly. Some mental processes might be more difficult or require more resources than others, yet there is no objective way to measure this. Mental effort is often equated with the number of processing steps a task is thought to require and the hypothetical availability of processing resources given competition from concurrent activities. There may be qualitatively different kinds of processes involved as well (Fisk, Scerbo, & Schneider, 1983; Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977). Controlled processing is slow, effortful, capacity-limited, and operator-controlled. It is required for novel or inconsistent information and when decisions are consciously derived. Automatic processing, which is typical of well-learned tasks, is fast, parallel, relatively effortless, not limited by the capacity of short-term memory, nor under direct operator control. Once developed, it is difficult for operators to inhibit it in the presence of eliciting conditions.

Rasmussen (1982) and others (Madni & Lyman, 1983; Tanaka, Buharali, & Sheridan, 1982) related different levels of operator behavior to variations in workload. Skill-based behaviors (conventional manual-control activities with immediate feedback about actions) may be performed automatically and contribute little to experienced workload. Rule-based behaviors (procedural activities, information processing, and short-term planning) involve higher level processing and more mental workload. Knowledge-based behaviors (complex interpretation, decision making, and development of novel solutions with limited or delayed feedback) require the highest level of processing and the greatest mental workload. Control decisions are transformed into low-workload mechanical action by exercising well-learned patterns of response or by actuating mechanized subsystems. Although a decision may be the result of complex mental processes, the control input itself may reflect a relatively trivial execution of it (in terms of workload). If well-defined rules exist for a task or if closed-loop control is required, then it is likely that it could be performed by a machine. This leaves for humans the more ambiguous tasks with indirect and delayed knowledge of results. Humans continue to out-perform machines on these tasks but at the cost of increased levels of mental workload. Thus, assigning skill-based and rule-based behaviors to machines may only shift the source of workload from direct sensation or physical control to interpretation, problem-solving, decision making, and prediction: high workload tasks.

Operator Skills

Whenever a task is performed, specific physical, sensory, and cognitive processing skills are required as well as a general knowledge base. Experienced operators may require less training (because they can use use established patterns of motor response), adopt more efficient strategies, and exert appropriate effort in a timely way, thereby minimizing workload. In addition, they are more likely to perceive task goals and performance criteria correctly. The above suggests that the workload experienced by practiced operators is substantially different from that experienced by novices. However, it is difficult to predict skilled performance on a task from its initial performance (Ackerman & Schneider, 1984). General abilities, previous experience, initial selection of strategies, and ability to understand instructions may be determining factors early in practice, while specific perceptual and motor abilities may be the limiting factors for trained operators. Furthermore, skills develop at different rates for different operators and different subtasks.

Extended, consistent practice changes mental processing qualitatively as well (Fisk, Scerbo, & Schneider, 1984; Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977). Training enables parallel processing, new abilities, and alternative strategies. It reduces the need for much of the conscious decision making evident early in practice, thereby reducing effort and apparent task difficulty. With training, operators develop mental models of the system allowing them to predict future states from present evidence. This frees them from needing information about system status on a moment-to-moment basis (Johanssen, et al, 1979), eliminating the performance of unnecessary activities and reducing workload. Psychomotor skills progress from continuous, conscious attention and activity focused on compensation and error correction to executing learned preprogrammed activities. Thus, the workload of skilled operators performing even simple manual control tasks stems from organizing and decision-making (Jex and Clement, 1979), rather than from properties of the signals being tracked or physical effort.

Experts tend to think in terms of larger units of activity than novices (National Research Council, 1982) to avoid being buried in minutiae. They may complete subtasks without conscious attention, recognize patterns of information, and initiate action sequences with single decisions. For example, with "touch-typing", associations between verbal stimuli, spatial keyboard positions, and movement trajectories for hands and fingers develop for different serial combinations of letters. Early in skill acquisition, visual supervision is required to position each finger. With practice, words and phrases may prompt "automatic" key sequences, with no conscious awareness of finger position or movement patterns. Depending on whether a task is viewed as a collection of unrelated and separate actions or as an integrated whole affects strategy selection and resource use.

Experts can relate one situation to other similar occurrences so they only have to notice and remember differences. Thus, unexpected events or failures may affect skilled operators differently than unskilled. Equipment failures, environmental changes, or errors may disrupt automatic sequences of behavior of trained operators (thereby increasing workload). On the other hand, the occurrence of predictable information would be less likely to interfere with ongoing task performance than would the occurrence of less predictable information (Broadbent, 1975). Thus, since little is predictable about a task to an inexperienced operator, the creation of workload by (apparently) unpredictable events may be responsibe for a significant part of the workload. Abnormalities may be overlooked because confused novices do not know what to look for and because controlling the basic system requires so much attention. Skilled operators may recover from their own errors or equipment failures with little increase in workload whereas unskilled operators might not notice a problem until it has become critical and may fail to compensate for it effectively. Operators experienced in the control of a basic mechanical system might not understand the additional functions and structure of an automated system. By contrast, one trained as a high-level user of a fully automated system might understand the computer-based management system, but have little knowledge of the underlying mechanical functions. Thus, failures that can be recognized and resolved (and the subsequent workload) will differ.

Performance

Performance may be thought of as either the result of workload (if workload is conceptualized as effort) or as an element of imposed workload (the moment-to-moment state of a system may be continually modified by the actions of operators). The act of performing a task not only provides input to the system, but it also creates observable outcomes which may be monitored and measured. However, addition, many measures of performance reflect the limitations, capabilities, and characteristics of the system controlled, rather than the behavior of the operator. Since machines now perform most of the repetitive stabilization and inner-loop control activities, evaluating operator's behavior (as distinguished from the response of the entire system) with traditional techniques has become increasingly difficult.

Workload and performance each depend on operators' responses to task manipulations (Wickens, 1984), rather than to the task demands alone. Models of human performance generally assume that performance improves monotonically as a function of resources invested and that experimental subjects always exert maximum effort. When performance changes occur following an increase or decrease in allocated resources, the task is said to be resource limited (Norman & Bobrow, 1975). As more resources are invested, perhaps in response to instructions to modulate resources among competing tasks to achieve specific levels (Gopher, Brickner & Navon, 1982), performance improves to the point at which the task is said to be data-limited (Norman & Bobrow, 1975).

In operational environments, however, task complexity allows alternative strategies and repetition may lead operators to exert less than maximum effort. Thus, poor performance may reflect extreme effort for impossible tasks or inadequate and inappropriate effort for easy tasks. Conversely, excellent performance may be found for easy tasks that impose low workload or difficult tasks that challenge operators to mobilize more resources. Nevertheless, the relationship between workload and performance is of practical importance because one may be sacrificed for the other; operators may shed tasks to maintain acceptable workload or increase effort to achieve consistent performance.

It is useful to discriminate tasks that cannot be performed (because of inadequate information, inaccessibility of controls, or hostile environment), from those that can be performed, but at the necessary cost of extreme effort. Furthermore, human operators have physiological and psychological needs that impact their ability to perform a task. Performance deteriorates rapidly when physiological needs for nourishment, sleep, comfort, and health are not met. Psychological factors, such as prolonged periods of high stress, fear, conflict, or inactivity may have a significant impact on performance as well. Invoking workload to explain the deterioration in performance associated with any of these factors is neither correct nor diagnostic.

Performance Feedback

Operators' perceptions of how well they are performing a task may influence their opinion of task requirements, suggest different strategies, or modify their subjective experiences. Correct assessment of the immediate situation depends on the currency and accuracy of information available about system state. However, the relationship between cause (operator action) and effect (change in system state) can be delayed or distorted if the isomorphism between operator actions and system state is masked by intervening computer-based systems or if information displays do not match operators' mental representations, leading to situations in which errors are likely. Finally, with either direct feedback (e.g., proprioceptive feedback from control movements) or knowledge of results (e.g. a display of vehicle deviation from the desired course), an operator's general knowledge and specific skills may be improved.

Thus, the response of a system is the product of intended task demands, modified by the environment in which the task is performed, filtered by the operator's perception, capacities, strategies, behaviors, and performance. It is this phenomenon, then, that is subjected to the experience of operators.

Experienced Workload

People often generate evaluations and commentaries about ongoing experiences. However, they rarely quantify, remember, or verbalize these fleeting impressions and experiences. They may be aware of their current behavior and sensations and the results of cognitive processes (but not the processes themselves) (Ericsson & Simon, 1980; Nisbett & Wilson, 1977). Only the most recently attended information may be directly accessible for verbal report; the contents of short term memory (Ericsson & Simon, 1980). However, additional information may be retrieved from long-term memory or recreated. Even though individuals have access to intermediate or final results of higher-level processing rather than to the processing itself, they describe their experiences as if they had access to the actual processes of cognition (Nisbett & Wilson, 1977). In addition, the intermediate steps of automatic processes that are typical of highly practiced behavior are completed without interpretation. Thus, their inputs and outputs are not available in short-term memory. This may suggest one reason why inexperienced operators report higher levels of workload than experienced operators. They are aware of intermediate processing and decision stages whereas skilled operators act automatically without conscious awareness. Thus, even though experimental subjects are generally willing to provide a numerical or descriptive rating, the subjective meaning of the information and contributing factors may not be clear. Nevertheless, only the operator can describe the experience of performing a task.

The importance of subjective workload experiences extends beyond an association with subjective ratings. They affect behavior, and thus performance, as well as physiological functions associated with stress or workload. If individuals feel loaded, then it is likely that they will behave as though they are. That is, they may adopt strategies appropriate for high workload conditions and experience physiological changes which may or may not be appropriate for the current situation. Conversely, objective performance and physiological functions can change without an operator's awareness, resulting in an inappropriately low level of effort. In fact, individual might feel they are working very hard even in the absence of external activity (Johanssen, et al, 1979). Objective measures exist for the evaluation of performance and physiological functions, however, it may not be possible to compare estimates of task demands or measures of performance across different activities because they do not share dimensions or measures in common. The phenomenological experiences of human performers, on the other hand, may combine many aspects of situations across a broad range of activities and memories of earlier experiences may provide a common basis for comparison. Thus, the experiences of operators may provide the only basis of comparison for unique and novel situations. Finally, specific task manipulations affect subjective experiences differently than they do other measures, thereby providing additional sources of information.

One benefit of differentiating subjective experience from imposed demands is methodological; it suggests one source of rating variability among individuals who experienced apparently identical situations. In addition, it is important to remember, that the subjective experience of workload is not necessarily the same as a subjective rating of workload. Information about an experience is available to the operator as the experience occurs. However, the fleeting experience of each moment is replaced by the experience of the following moment. Information available for recall is limited to whatever was stored incidentally or deliberately in long term memory.

MEASURES AND PREDICTORS OF WORKLOAD

To a very great degree, the assessment of workload depends on its conceptualization (Moray, 1979). Most researchers agree it is a composite concept reflecting various contributing factors related to the task, internal human dispositions, and skill level (Sanders, 1979). In practice, however, each researcher's definition is somewhat different and practical circumstances may impose constraints on the measurement tools that might be applied. Research has shown excellent agreement among some workload measures and manipulations of different task parameters in some situations, and none in others. One reason for the lack of agreement might be that many commonly used measures are inappropriate, unreliable, or insufficiently sensitive. For those measures that are valid and reliable, however, the discrepancy may occur because different measures selectively reflect different dimensions of the complex phenomenon of workload. In addition, many measures were developed without a theoretical foundations, thus they cannot predict what might happen under different circumstances. In most cases, the development and validation of measures is circular. If different tasks produce variations in a measure, then it is thought to have "succeeded". If not, then it "failed". Because there are no standardized tasks that impose known levels of workload and there is no way to determine independently whether the task imposed the predicted levels of workload or the subject experienced them as expected, there are no benchmarks against which proposed measures or theories can be tested. Research is underway to address this problem, however. For aeronautical research, laboratory and simulation experiments, and pilot opinion surveys have been used to create flight scenarios that will impose predictable levels of workload (Hart & Bortolussi, 1983; Kantowitz, et. al, 1984). In addition, a method for evaluating workload metrics has been developed (Shingledecker, Crabtree & Acton, 1982) so that measures can be evaluated against criterion laboratory tasks that vary in sensitivity, diagnosticity, intrusiveness, operator acceptablility, and ease of instrumentation. The tasks represent the functional components of human information processing in operational tasks as suggested by the multiple resource model.

Subjective Ratings

Subjective ratings may come closest to tapping the essence of mental workload and provide the most generally valid and sensitive indicator (Johnanssen, et al, 1979; Sheridan & Stassen, 1979). There are two sources of subjective evaluation: operators themselves or observers. Evaluations may be obtained while a task is being performed or after it is completed. The intervals of time evaluated might represent several minutes or many hours. Available techniques include: (1) unidimensional numerical ratings given with or without behavioral anchors or verbal labels; (2) multi-dimensional evaluations of different task features; (3) rank-ordering of experiences with respect to workload; and (4) task-specific checklists, questionnaires and verbal protocols. Although ratings been used, studied, and critiqued extensively (Moray, 1982; Wierwille & Williges, 1978), methodological and theoretical problems remain. In fact, some researchers deny their value at all, considering them to be examples of the discredited practice of introspection. However, the more generally accepted view is that they provide a significant source of information.

Operator Ratings

Operators can normally provide verbal or numeric evaluations of task and task elements. The information upon which evaluations are based might include the results of information processing, perception, memory, overt behaviors, and feelings associated with an activity. Ratings reflect a subset of the information available during task performance and may not suggest which factors were considered in forming the evaluation or explain the underlying cognitive processes. Thus, subjective reports may contribute little to theoretical models. Nevertheless, they may provide the only source of information about the effect of performing a task on operators and do provide information about the integrated effects of many possible workload attributes. Even for very different activities, the remembered or reconstructed subjective experiences of operators might provide a common point of comparison.

One difficulty encountered in evaluating or equating any abstract concept (such as workload) or extrapolating average or typical experiences from exemplars is that specific instances might not be related in memory. For example, it is unlikely that instances of high, medium, and low workload are accumulated from individuals' life experiences to serve as a mental reference scale labeled "workload". Rather, activities that have elements in common can be compared with respect to shared qualities and information remembered from similar experiences can be generalized by applying heuristic principles that reduce assessment and prediction to simpler judgemental operations. Although these heuristic rules are generally useful, they may lead to systematic errors (Tversky & Kahneman, 1974). For example, an individual might have experienced high levels of workload when performing mental arithmetic in the past. Thus, he might conclude that the workload of yet another arithmetic task was high even though his actual behavior and experience might have suggested otherwise. Finally, people are more likely to equate some task manipulations with workload variations than others. Thus, some task characteristics that influence performance may not influence subjective experiences and individuals may be sensitive to variables that do not lead to performance variations (Wickens & Yeh, 1982; 1983).

Calibration of raters. Information is rarely given to raters about the accuracy or validity of their ratings, even though providing guidance to shape strategies and performance is a common practice. In fact, it would be considered a breach of protocol in most experimental settings to inform a subject that a rating was "wrong", or that the task features that prompted a specific rating were irrelevant. Thus, it may be difficult for raters to adopt the criteria or focus of the designer of a task or evaluation procedure. If raters are to act as instruments for recording levels of workload, then why not calibrate them to insure standardized, interpretable, and relevant output? This could be accomplished by identifying, defining, and demonstrating different levels of relevant dimensions and informing raters about their accuracy with respect to the quantities of interest. Standard reference points for categorical values or anchor points could be identified or demonstrated and comparisons limited to tasks that share elements in common with the reference tasks.

The great success of the Cooper-Harper rating scale for aircraft handling characteristics (Cooper & Harper, 1969), which has been used extensively by engineers and test pilots for preliminary and operational test and evaluation of aircraft, suggests the applicability of this concept. Concrete information and training are provided about how to use the scale, elements are operationally defined, and the "feel" charcteristic of different scale values is demonstrated in a variable stability aircraft. This calibrates test pilots to serve as recording instruments sensitive to factors considered relevant.

Timing Since verbal reports and ratings are necessarily based on memory of the continuously receding past, obtaining them frequently might seem desirable. Yet, this could substantially interfere with task performance. The key issue might not be how fresh a memory is, but how much incidental memorizing occurred during the task and the relevance of the operator's memories. For example, it has been found that ratings obtained immediately after the completion of a block of memory trials or after a delay of 15 min were not significantly different (Eggemeier, Crabtree, & LaPointe, 1983), and both discriminated workload-related primary task differences. Under favorable circumstances, requiring verbal ratings while performing a task might impose little additional workload. However, even for retrospective estimates, some mental resources must be required to remember information for later recall. Even this might alter an operator's normal mode of processing. Thus, there is a tradeoff between the possibility of task interference (caused by remembering information to provide accurate ratings or providing ratings during task performance) and the possibility that nothing will be remembered incidentally.

Ratings are normally given about what occurred during an activity or period of time. Thus, the existence of similar reference activities and whether the interval had a logical beginning, middle and end for which requirements, effort, and success could be assessed are salient. Many tasks are carried out in discrete, functionally-related units. Thus, operators should be able to evaluate or remember the workload of a meaningful segment more easily than an arbitrary interval that includes unrelated activities or an interval that is not distinctive. However, if an unexpected or remarkable event occurs during an interval, it may influence ratings more than its relative duration warrants. If an activity is retrospectively recreated, some temporal aspects of the original event (such as the length and pacing of task elements. may not included. Relatively long periods of time may be mentally reviewed in seconds and different levels and types of detail may be possible. For example, "time pressure" may be represented in an evaluation only if its occurrence during the original experience was remembered.

Quantification. Ratings can reflect either a quantified (but nonverbal) subjective experience or a deliberate, verbal evaluation related to a numerical value. They may be obtained in a variety of formats; numerical values, magnitude judgments expressed as distances along a continuum, or selection among alternative descriptors. Scale extremes may be labeled with descriptive adjectives or numerical values. They may be subdivided into equal intervals (or not) and, if they are, the intervals may or may not be labeled. It is rare that the absolute value of a rating carries more meaning than the relationships among ratings given for related events, due to limitations in scaling procedures, and absence of common anchor points and scale intervals across tasks.

Single-dimension scales. Many applications involve a single numerical estimate of workload. For example, a magnitude estimation technique, adapted from classical psychophysics, was used to assess the workload of tasks presented singly and in pairs (Gopher & Braune, 1983). One task was identified as the reference and the other tasks were compared to it. The transformed numerical ratings were significantly correlated with task difficulty predictions based in the multiple resources theory, suggesting that workload magnitudes could be evaluated as if they ranged along a physical continuum. In other laboratory studies (Borg, 1978), the subjective difficulty of physically and mentally loading tasks was evaluated using various scaling techniques including magnitude estimation. A single numerical rating of overall workload was obtained after each segment (Childress, Hart, & Bortolussi, 1982) and at one-minute intervals during simulated flight with a 10-point scale (Rehmann, Stein, & Rosenberg, 1983). In flight, single numerical workload ratings, prompted by an observer-pilot, were obtained during full-mission certification flights for the Airbus A-300 and A-310 aircraft using a five-point rating scale for the pilots and a seven-point scale for the observers (Speyer & Fort, 1982).

Multi-dimensional scales. More often, evaluations are made of several task features in addition to (or instead of) a global workload rating, acknowledging the multi-dimensional nature of workload. This requires evaluators to decompose their experience and consider different aspects individually. Since a multi-attribute analysis makes this activity explicit and identifies the dimensions to consider, it may provide information about the subjective structure of the workload experience. Thus, it will protray individual differences in definition if the appropriate workload-related dimensions are selected. The alternative of obtaining a single value masks the fact that these other attributes (which exist even if not explicitly rated) impact individual raters' workload experiences in different ways. In some cases, the dimensions that rated are task-specific. For example, Boeing Aircraft Company developed a rating scale to evaluate the B-757 and B-767 aircraft (Ruggiero & Fadden, 1982). Pilots identified the amounts of different kinds of workload (e.g. mental effort, physical difficulty, time required, etc) imposed by flight task components (e.g., navigation, flight management, monitoring, communications, etc.) for different mission segments. Evaluations were made in comparison to a reference aircraft by selecting one of seven discrete levels (from "much more" to "same" and "much less").

Several multi-dimensional rating scales for workload evolved from the Cooper-Harper scale for aircraft handling qualities (Cooper & Harper, 1969). The original scale was arranged in a decision-tree, leading raters through a progression of simple decisions to one of 10 numerical ratings. Subsequent research was conducted to determine the meanings of the descriptors to pilots, their association with specific task parameters, the subjective distances of the levels from each other, and distributions of ratings (McDonnell, 1969). Although several researchers have reported a moderately high correlation between Cooper-Harper ratings and subjective and objective measures of workload in simulated aircraft control tasks (Childress, Hart & Bortolussi, 1982; Connor & Wierwille, 1983), the scale was not designed for workload assessment. Thus, in other applications, the wording of the scale was modified so as to relate more directly to workload (Sheridan & Simpson, 1979; Wierwille, Skipper & Reiger, 1984). Although the structure of the scale itself makes the decision task seem easier and significant relationships have been found with experimental variations in pilot workload, the fact that each choice point in different versions of the scale requires a decision based on an evaluation of a different workload-related dimension poses a problem. On one such scale, for example, (Wierwille, Skipper, & Casali, 1984) successive decisions are based on: (1) likelihood of errors, (2) mental workload, (3) perceived difficulty, and (4) effort required versus performance attained. The single workload rating is, in fact, the result of an implicit multi-dimensional rating process that addresses different aspects of imposed workload, system response, and operator experience. However, there is no rationale presented for the selection or ordering of the factors. Because different factors may be relevant to different individuals it might be more appropriate to vary the order in which decisions are made to reflect the subjective importance of the factors to individuals or groups of individuals.

Many other rating techniques involve evaluation of two or three relevant factors. The Workload Compensation Index and Technical Effectiveness (WCI/TE) scales of the Missions Operability Assessment Technique (Helm & Donnell, 1978; Connor & Wierwille, 1983) have been used to evaluate several aircraft and simulated approaches. Multi-attribute utility functions were derived allowing decisions about system operability from predictions and ratings. The Subjective Workload Assessment Technique (SWAT) was based on the assumption that workload experiences can be described by three dimensions ("spare" time, mental effort, and stress) (Eggemeier, 1981; Eggemeier et al, 1982; Reid, et al, 1981; 1982). The three dimensions were suggested by Sheridan and Simpson (1979) in their version of a Cooper-Harper-scale for mental workload. SWAT requires the preliminary sorting of 27 combinations of three levels of each of three dimensions with respect to workload. Conjoint scaling procedures are used to derive a 27-point interval rating scale. During different tasks, then, operators rate the time pressure, mental effort, and stress experienced on three-point scales. These three ratings are then converted to the appropriate interval scale value for overall workload. This technique has been applied in laboratory and simulation environments and has been found to be sensitive to variations in aircrew communications load (Reid, et al, 1981) and short-term memory (Eggemeier, et al, 1982), with good inter-rater reliabilities. Although it is receiving widespread use, the initial sorting procedure is awkward and time consuming and the statistical analysis requires an elaborate computer program. In addition, the assumption that people can predict accurately the workload imposed by 27 combinations of abstract variables may not be justified, nor might the assumption that the three dimensions are subjectively orthogonal (Boyd, 1983). Finally, three factors might not be sufficient to characterize individual experiences and definitions (Derrick, 1983; Hart, 1982)

One advantage of subjective ratings is that operators <u>can</u> let their experiences influence their judgements, thereby taking into account whatever they consider relevant. The disadvantage is the potential for between-rater variability due to individual differences. One rating technique has been developed that incorporates information about a priori rater biases about nine workload-related dimensions into a derived workload score. The dimensions were selected on the basis of preliminary laboratory and simulation research (Hart, 1982; Hauser, Childress & Hart, 1983) to include those considered relevant by most individuals. They are: task difficulty, time pressure, performance, mental effort, physical effort, fatigue, frustration, stress, and activity type. Independence between the dimensions was not assumed, as some of them have, in fact, been found to covary under different experimental conditions. When this occurs, their influence is magnified, and when it does not, it is reduced - - an acceptable loss of statistical power to achieve a realistic perspective of the subject's experience. Subjects compare each of nine factors to every other one by making a simple decision for each pair: which of the two factors is more relevant to workload. The relative importance of each dimension is then used to compute a weighted combination of ratings on each the nine scales after different experimental tasks (Hart, Battiste, & Lester, 1984; Hart, Sellers, & Guthart, 1984; Kantowitz, et. al, 1983; 1984; Miller & Hart, 1984). In every application, the weighted combination of ratings maintained the significant relationships among experimental conditions (as estimated by an overall workload rating or a secondary-task measure) but the between-subject variability was reduced by as much as 50%. It is assumed that the subjective biases that lead different individuals to focus on some aspects of an experience more than others when giving a workload evaluation are masked by a single numerical evaluation of workload, but contribute to between-subject variability. Explicitly using these subjective biases to weight the importance of different dimensions results in a summary estimate of workload that represents the experience of each individual. This technique does not have the statistical power of SWAT, however it may provide a useful alternative. It is simpler to use, reflects a broader spectrum of relevant variables, and requires fewer statistical assumptions.

Psychometric Considerations. It is in the area of quantification that many problems with subjective ratings occur. Even though the absolute value of a rating can be recorded with (artifically) great fidelity and precision, the underlying psychometric function is rarely known. Few scales have a true "zero" point, their upper limits are often undefined and may vary with the task and operator. Scale increments (whether they are expressed in psychological, mathematical, verbal, or spatial terms), may not be equal in size. Some of the psychometric techniques used to improve scale development from a statistical point of view include magnitude estimation (Borg, 1978; Gopher & Braune, 1982), the method of equal-appearing intervals (Hicks & Wierwille, 1979), and conjoint measurement (Eggemeier, et al, 1982, 1983; Helm & Donnell, 1978).

Advantages and disadvantages. Even though scaling problems continue to plague the use of subjective ratings scales, their practical utility and the wealth of information they provide outweigh their drawbacks. They can be applied in any environment, either during or soon after intervals of interest. They are acceptable to most operators, researchers, and decision-makers, havingface validity and intuitive appeal. They exhibit good within-subject reliability, and a surprising between-subject reliability considering the potential for diverse opinions. They are easy to implement and score, and, with some exceptions, to analyze. Finally, they provide one of the least interfering methods.

Their drawbacks include scaling problems and limitations on the information available to be experienced and remembered. Scales are often task-specific and it is rare that the raw numeric values obtained in one setting can be applied directly to another. In many cases, they provide no more than ordinal information, allowing comparisons within, but not between, different tasks or environments and they have limited diagnostic and predictive value. In spite of these problems, ratings still provide the most acceptable and widely useful method for workload assessment and have potential application in prediction.

Observer ratings

Observers can monitor the behavior of operators to determine the load imposed on them and their probable experiences. They may use checklists, written records, rating scales, and video and audio recorders to quantify and record their observations. However, they must be experienced in the target activities to appreciate the significance of operators' behaviors and familiar with the rating procedures. Since observers must rely on observable activity, this technique is not useful when information processing and monitoring are the predominant activities. Even if activities are observable, they may be associated with different subjective significance for operators than observers. Observers may unburden the crew members from the necessity of providing on-line evaluations, however their presence may be a source of interference or additional stress. On the other hand, if several operators are being monitored, the observer may be subject to considerably more workload than the operators. This problem could be solved by recording events for later analysis by observers or the crewmembers themselves. Finally, just as ratings provided by individual operators are subject to biases, so are observer evaluations.

Although this technique has limitations, it is a useful source of information to complement crewmember ratings and provides an alternative if they cannot be obtained. In addition, on-line or retrospective analyses by trained observers can provide as much information about task demands, structure, environment, procedures, and crew interactions as the participants might provide, even though the observers did not perform the task personally. In fact, an observer might notice more than can busy operators. Under some circumstances, the correlation between the ratings of an experimental subject and another individual who understands the information and structure of the task can be almost perfect (Gopher & Braune, 1983). An observer can be as accurate as an operator in identifying factors that determine behavior (Nisbett & Wilson, 1977) even though they can only guess about the mental effort expended, the physiological consequences of performance, and operators' subjective experiences. For example, during certification flights for the Airbus A-300 aircraft, it was found that operator and observer ratings were very similar (Speyer & Fort, 1982).

Primary Task Performance as a Measure of Workload

Even though system performance may be affected by operator workload, it is not itself workload (Rouse, 1979). It reflects the combined responses of human operators and system hardware. Thus, the use of performance measures to infer operator workload may be inappropriate, in spite of the fact that improving or maintaining system performance is the most common motive for assessing, predicting or modifying workload. With a simple laboratory task, the mapping of human responses into measured performance is immediate and direct. Response times can be recorded with millisecond accuracy, directly reflecting the overt behavior of experimental subjects. The relationships among task demands, human behavior, and performance relatively direct. For complex systems, or ones in which the operator acts as a supervisor, however, the response of the entire system may be the only observable behavior. It may reflect hardware and software characteristics (e.g. handling qualities, control dynamics, lags, inertia, and the combined input from automated sub-systems) as much as the behavior and state of the operator. Thus, only those aspects of complex system performance that allow a direct mapping between operator behavior and measurable performance have the potential of reflecting an operator's workload.

Measures of performance may not reflect the hypothesized association between workload and time pressure. Until it is no longer possible to make responses fast enough, response time and accuracy are more likely to reflect the difficulty of a task than presentation rate. If operators' responses lag behind arriving tasks, then performance may be based on operators' memories of leftover tasks and their ability to reorganize behavior to complete these tasks while beginning more recent activities. It is also possible that operators make a strategic decision to ignore occasional tasks in order to catch up. These alternatives may or may not lead to performance decrements. Even with sufficient time, stressed or busy operators may overestimate how quickly time passes (Hart, McPherson, & Loomis, 1978), causing them to experience greater time pressure than exists. This might cause them to adopt inappropriate strategies (e.g. hurrying, experiencing stress, or task shedding), thereby degrading performance or imposing on themselves unreasonable requirements for speed.

Different types of performance decrements might be characteristic of specific tasks and performance on some subtasks might be degraded by competing demands for operator's attention more than others, providing an objective indication of increased workload. For example, it has been shown that people tend to lose track of time when their attention is diverted elsewhere (Gunning, 1978; Hart, McPherson, & Loomis, 1978). Many operational tasks involve timing, either implicitly or explicitly: estimating whether one is on schedule, predicting the time available to complete additional tasks, estimating the time required to complete a task, and coordinating tasks in space and time. Accurate timekeeping requires continuous attention to the passage of time; inattention results in underestimation. Thus, performance of tasks that require timing could be monitored to determine the attention demands of concurrently performed activities. Other timing activities, such as those that involve the automatic performance of rhythmic or coordinated actions that do not involve reference to units of clock time, may require a lower level of attention. Thus, they will be disrupted by extreme levels of concurrent task demands.

Communication with other crew members and support personnel is required in many operational environments. It is another activity in which operator behavior can be monitored directly, providing another potential measure of performance sensitive to overall workload levels. Different communications tasks have been found, analytically, subjectively, and empirically, to reflect different levels of workload (Acton, et al, 1983; Hart & Bortolussi, 1983; Hart, Hauser, & Lester, 1984; Shingledecker, et al, 1982). Their performance requires not only receiving and understanding the messages, but also completing additional activities prompted by their content.

The occurrence of errors is usually supposed to reflect an increase in workload. However, errors may occur as often from too little workload (due to inattention and loss of vigilence) as from too much. Furthermore, it is difficult to induce errors experimentally, so it has proven impossible to systematically relate their occurrence to different levels or sources of workload. Alternatively, detecting, diagnosing, and resolving errors may substantially increase the difficulty of a task and the amount of effort required to complete it. A pilot opinion survey suggested that pilots experience a 10 to 50% increase in ongoing workload levels with the occurrence of different types of pilot and system errors (Hart & Bortolussi, 1983). Thus, errors may prove to be a significant source of workload as well as a consequence of it.

Measures of control error, variability, and reversals might reflect workload levels in tasks that require continuous, direct control, as might increased response time or decreased accuracy in discrete control tasks. Wickens (1984) recently suggested that the workload margin of a complex task could be determined by individually manipulating the difficulty of specific primary task parameters, thereby depleting different resources. If sufficient variations in difficulty are possible, this procedure empirically evaluates how close an operator is to being saturated by the nominal levels of task difficulty.

Advantages and Disadvantages.

The primary advantage of system performance measures is they reflect how well task objectives were satisfied. However, they are insensitive to variations of workload that lie within an operator's capacity to recruit additional resources to maintain a consistent level. In addition, performance decrements may reflect extreme (but unsuccessful) effort in response to excessive task demands, lack of attention to low or moderate task demands, or inappropriate selection of strategies. Conversely, excellent performance may reflect an appropriate level of effort for an easy task or extreme effort applied inappropriately. The effort required to achieve or improve performance is not the same for different levels of performance. Improving task performance from adequate to good might require a moderate increase in effort, whereas extreme effort and lengthy training might be required to improve from very good to perfect. In fact, many tasks have a maximum level beyond which no further investment of effort could improve performance. Inconsistencies in the mapping of task variables onto objective system changes suggest measures of performance alone do not reflect the cost of producing the obtained level of performance, the capacity remaining to perform additional tasks, or the subjective experiences of operators. Single measures of performance, in particular, are not diagnostic and do not reflect strategy changes. However multiple performance measures might reflect operators' strategies, suggest specific areas of overload, and the existence of an overload or nonoverload dichotomy.

Performance measures are often already in existence (and are not intrusive to the operator), but they may require additional instrumentation in operational environments. Furthermore, many measures of performance are task-specific and it is difficult to compare performances across tasks that do not provide common measures or for which similar measures have different sensitivities, distributions, or meanings. If raw measures of performance are obscured by computing proportions, difference scores, or standard scores, the fact that underlying measures are not related may not be obvious (Kantowitz & Knight, 1978), but the possibility of inappropriate comparisons remains. Finally difficulty manipulations may result in qualitatively different behaviors and workload, while overt responses are identical. For example, reaction time has been used as the primary measure for an incredibly diverse array of tasks and subtasks, yet the simple, seductively objective, and precise value reflects a host of underlying processes, structures, strategies, experiences, distributions, and limits that are invisible except by inference.

Analysis of Workload by Secondary Tasks

Another way to use measures of performance to assess workload is to impose a concurrent secondary task (Bahrick, Nobel, & Fitts, 1954). The tasks that have been used as secondary tasks are usually drawn from laboratory research, providing a relatively direct mapping between operator behavior and measurable performance. Thus, secondary task performance can reflect the instantaneous capacity of the operator whereas measures of primary task performance may reflect preprogrammed routines, system lags, and vehicle dynamics of the overall complex system. In addition, predictions about the underlying processes and behavior for such tasks can be made with reference to extensive theoretical research. Secondary task performance is presumed to consume whatever resources remain from the primary task, providing an indirect estimate of the capacity demanded by the primary task. Unlike dual-task paradigms, one task is emphasized through instructions, rewards, or intrinsic motivations. The other is performed in the operator's "free time". This implies that operators can assess their primary task performance levels accurately enough to permit such continuous, dynamic allocation of resources.

If there is a single undifferentiated pool of resources to be allocated among activities, then one standard secondary task could serve as a common workload "yardstick", its performance being proportional to the resources remaining from a range of primary tasks. No such universal task has been found, however. Instead, different tasks have been found to be selectively sensitive depending on the pattern of requirements shared with specific primary tasks (Wickens, Sandry & Vidulich, 1983). Task interference may occur at different information processing stages, because of insufficient resources to accomodate a particular task combination, or a physical impossibility. In addition, there are individual differences in time-sharing abilities and strategies (Ackerman & Schneider, 1984; Damos, 1984; Gopher & North, 1977; Lansman & Hunt, 1982).

Adopting a theory-based approach rather than relying on intuitions greatly improves the diagnostic power of this paradigm. The first step requires an analysis of the primary task to select secondary tasks that will tap common resources. Since every task is composed of many demands that vary along different dimensions, it is impossible to construct a secondary task that taps just one primary task component, however. Thus, decrements on several secondary tasks imposed on one primary task provides a pattern of converging information about specific sources of loading. It is usually considered desirable that secondary tasks should not interfere physically with primary tasks. This implies that some types of competition are desirable (e. g., requiring the same mental resources) whereas others are not (e.g., moving in two different directions at the same time). An alternative approach varies the intensity of effort required on primary or secondary tasks by manipulating their difficulty (Kantowitz & Knight, 1976; Kantowitz et al, 1984) or the level of required performance (Gopher, Brickner, & Navon, 1982). Finally, the timing requirements of concurrent tasks is an important aspect of their demand characteristics. For example, some tasks may be so successfully interwoven that momentary lapses of attention to one to perform the other can be accomodated through motor coordination and scheduling. Other tasks may require continuous attention so that single-task performance levels cannot be maintained without consistent attention.

Specific Methods

Hundreds of tasks have been used to measure the workload imposed by other laboratory tasks, part-task and full-mission simulations and operational activities. Descriptions of tasks used for this purpose have been published elsewhere (Jex & Clement, 1979; Ogden, Levine, & Eisner, 1979; Wierwille & Williges, 1978), thus, the review offered below will be selective and more cursory than the popularity of the technique warrants.

Imbedded tasks. There is continuing interest in identifying workload-sensitive subtasks that occur naturally as components of a variety of jobs. These can be monitored a relevant, unobtrusive and acceptable alternatives to artificial, additional activities. Communications and time estimation, for example, have been found to reflect the levels of workload imposed by concurrent tasks and they can be logically included in many operational activities. Not only do they have face validity and operational relevance, but they measure operator behavior directly and can be obtained in operational situations where additional activities cannot be imposed.

Reaction Time Tasks. This secondary task requires a rapid response to the appearance of a visual or auditory stimulus. Although single alternative tasks have been used (Connor & Wierwille, 1983), the more typical application involves multiple alternatives (Gopher & North, 1974; Kantowitz, et al, 1983, 1984; Kantowitz & Knight, 1976a). The latter is preferred because a range of difficulties can be generated by manipulating the number of alternatives according to known psychological principles and because it imposes additional mental requirements that a simple stimulus/response requirement does not. While single-alternative tasks have limited sensitivity (Connor & Wierwille, 1983), multiple-choice tasks have discriminated among relatively subtle primary tasks load levels ranging from incidental learning (Fisk, Derrick, & Schneider, 1983) to component flight tasks (Kantowitz, et al, 1983; 1984). This task has the advantage of simplicity and a strong theoretical foundation. Its primary drawback is that stimuli are not presented continuously and thus reflect no more than the momentary level of workload. If they can be synchronized with the occurrence of primary task components of interest (Kantowitz et al, 1983), their diagnostic power and sensitivity would be improved considerably.

Memory. Since many operational tasks are predominantly cognitive, the choice of a secondary task requiring short-term memory is obvious. A commonly used paradigm, the Sternberg memory search task (Sternberg, 1969; 1975), was developed originally to investigate stages of human information processing. Subjects remember one or more items (the memory set) and compare successive items (probes) to the memory set. If the probe is a member of the memory set, a positive response is made. If not, a negative response is made. A serial exhaustive search through memory characterizes task performance. The slope of the response-time/memory-set-size function reflects a constant increment in response time for each additional memory set item. It is assumed the memory search continues to require a constant amount of processing time (leaving the slope unchanged), but the intercept is elevated by the requirement to time-share this task with another. Although these relationships have been found in many applications, selective interactions with different perceptual and response load manipulations (Micalizzi & Wickens, 1980) and insensitivity to specific manipulations of pilot workload (Connor & Wierwille, 1983) are also common. Under conditions of particularly high workload, operators may withhold responses completely, significantly reducing the usefulness of the measure. This occurred in a high fidelity simulation (Hemingway, 1984) and inflight (Schiflett, 1980) when the memory search task was introduced to assess the workload of different aircraft handling qualities and display configurations. If responses could be obtained consistently, and if the information to be remembered and evaluated could be presented as an integral part of the primary task (to insure its performance), then it might prove to be a more useful assessment tool. The primary advantage of this task is the wealth of experimental evidence available about performance under a variety of circumstances.

Monitoring. Several auditory and visual monitoring tasks have been used to measure the workload of other laboratory and simulation tasks. Ephrath and Curry (1977) required pilots to perform a visual failure detection task while performing a simulated low-visibility approach. The secondary task was most effective when the failure occurred in a monitored or controlled axis and workload was somewhat elevated. Static or dynamic monitoring tasks were performed in combination with five other laboratory tasks (Chiles, Jennings, & Alluisi, 1978). Monitoring performance was used to compute the workload scale against which other task combinations were evaluated. The difficulty of a monitoring task can be manipulated over a wide range and the consistency of attention required can be varied as well, satisfying two of the requirements for secondary tasks. However, the task may interfer in undesirable ways with primary task performance if presented in a conflicting sensory modality and application in an operational environment may be a problem.

Tracking. The use of pursuit or compensatory manual control tasks to evaluate the workload of other tasks has been limited to laboratory settings, where it has been used extensively. Different manipulations (such as bandwidth, frequency, and axes controlled) have been used in combination with other activities to investigate models of human performance (Brickner & Gopher, 1981; Wickens, Sandry, & Vidulich, 1983) and develop and validate a variety of workload rating scales. Its primary advantages are that it is continuous, the sources and magnitudes of difficulty can be varied over a wide range, and operator behavior can be measured directly. In an operational environment, such as flying, performance on one control might be monitored to indicate the capacity remaining from other required tasks, providing an imbedded "secondary" task.

Adaptive tasks. One problem in interpreting secondary task performance is that it might alter primary task performance (Fisk, Derrick, & Schneider, 1983; Wierwille & Williges, 1978). To overcome this difficulty, the idea of presenting a secondary task only when primary task performance is within an acceptable tolerance was introduced (Kelly & Wargo, 1967). Alternatively, the difficulty of the secondary task could be varied dynamically as a function of primary task performance (Jex & Clement, 1979). Techniques presented cross-adaptively include critical instability tracking tasks (disturbances are varied dynamically) or digit processing (presentation rate). They have been applied in operational, laboratory, and simulation environments and have some advantages over nonadaptive tasks, however they are relatively difficult to implement and calibrate.

Time estimation. Because it is difficult to concentrate on the passage of time in the presence of any other activity, tapping at a regular rate, producing specific intervals of time, or retrospectively estimating the duration of an activity have served as secondary task measures of ongoing task workload (Casali & Wierwille, 1982, 1983; Connor & Wierwille, 1983; Gunning, 1978; Hart, McPherson & Loomis, 1978; Rahimi & Wierwille, 1982). As primary task demands draw attention away from timekeeping, clock time continues but the operator's perception of it does not. Thus, the amount of time that passes is underestimated with the result that time productions increase and verbal estimates decrease in length and the variability of successive estimates increases. Because it requires little instrumentation or training and can be included as a normal part of an operator's duties it has certain practical advantages. Although time estimations are relatively consistent within individuals (providing stable baseline levels), they reflect momentary fluctuations in workload imposed by competing activities (providing a sensitive indicator). The disadvantages includes the need for repeated presentations, the fact that variations in workload are expressed relatively (with respect to an individual's baseline rather than absolutely) and insensitivity during intervals of nonperformance (a problem common to all periodic techniques).

Advantages and Disadvantages

It is difficult to generalize about secondary tasks because they represent such a broad range of activities. However, they should have the following

properties: face validity, insensitivity to some variables (such as practice) and sensitivity to others (determined by the research questions), simplicity, reliability, noninteractivity with the primary task and frequent and direct scoring of operator behavior. Well-chosen secondary tasks are more likely to measure operator reserve capacity than primary task measures and may predict performance under other circumstances. They may provide different information about the workload of a complex task than subjective ratings do, as each is sensitive to different task variables (Derrick, 1983; Wickens & Yeh, 1982; 1983). They may be the only objective measure sensitive to variations in low levels of workload because they provide sufficient additional loading to produce measurable performance changes. Finally, identifying subtasks that occur as part of the primary task itself that can serve as "secondary" task measures of primary task workload without imposing additional artificial requirements should expand the utility of this technique. A disadvantage of this might be the necessary task-dependence thus engendered.

Since no single secondary task yardstick has emerged that is appropriate for all primary tasks, the initial promise of this technique has not been achieved. Different secondary tasks address different questions and there are pragmatic problems associated with how and when to impose them. Adding any additional task has at least some minimal processing cost, and many tasks interfere with primary task performance because of the structure of concurrent tasks or operators' attention allocation policies. In addition, secondary tasks may change behavior on the primary task qualitatively as well as quantitatively. In fact, the combined task may have properties not present in either task performed separately. In an operational environment, the significant advantages of using a laboratory task (for which theory-based predictions can be made with assurance), are outweighed by the disadvantages of requiring obviously unrelated and artificial activities in addition to normal duties. In the majority of operational environments in which such a task has been used, operators simply ignored or forgot it with significant frequency, thereby reducing its sensitivity.

Physiological Measures

Physiological measures of workload have been proposed because they offer a direct indication of operators' responses to the demands placed on them. The underlying assumption is that measurable, involuntary, physiological changes occur as the physical and mental demands of a task vary. In addition, since emotional stress may accompany increased workload, physiological indicators of arousal might provide an indirect method of assessent. There are two major classes of physiological measures: (1) measures of emotional and physical activation (e.g., heart rate and variability, respiration, galvanic skin response, muscle tension, pupil size, and vocal stress) and (2) measures of mental and perceptual processing (e.g., evoked cortical potentials and eye point of regard). Measures of voluntary activity (such as hand or leg movement) are not generally considered to be "physiological" measures.

Physiological measures can be obtained unobtrusively, they rarely interfer with primary task performance, and many vary with sufficient frequency to be sensitive to momentary shifts in workload. Unfortunately, their use has met with only limited success (see O'Donnell, 1979; Wierwille & Williges, 1978); no single measure or set of measures covaries with other indices of workload consistently enough to serve as a standard. For a given measure, individual differences in responses to various task manipulations among individuals create problems, and different measures respond selectively and independently to different aspects of activities. In addition, stresses placed on operators produce psychological and physiological effects that reflect a non-specific response to any demand. The sources of stress may be from the environment in which a task is performed or the emotional reaction of the operator. The latter may be related to the task either directly or indirectly or to events that are not job-related. Finally, while it is relatively easy to measure physical activity and effort, it is considerably more difficult to detect cognitive activities. Thus, while it may be relatively easy to obtain measures of physiological functions, it may be difficult to relate them to variations in workload. Physiological fluctuations are not task specific, reflecting physical effort and emotional responses in a general way. Finally, most techniques require special equipment and expertise, and may be impractical in applied environments.

Measures of cardiac functioning

Many commonly used physiological measures involve monitoring different attributes of the circulatory system. Heart rate, heart rate variability, blood pressure, and respiration have each been thought to reflect workload either directly or indirectly. As the heart muscle tenses and relaxes circulating blood through the system, variations in the sound of a heart beat and residual electrical potentials can be recorded on the skin to measure different features of the waveform. If diagnostic precision is not required, then measures of cardiac functioning, like subjective ratings, may provide an integrated indication of the total impact of an experience on an operator. Unlike subjective ratings (that reflect an operator's conscious evaluation of a situation), however, some physiological measures may reflect the unconscious, involuntary effect of imposed task demands and an operator's emotional reaction to them.

Heart rate. The average number of heart beats per minute is easy to record and has been used to measure physical and mental stress in many studies and to estimate workload specifically in relatively fewer studies. The expectation has been that heart rate will increase as workload is increased. However, this measure rarely has demonstrated adequate sensitivity to empirical changes in imposed task demands or operator behavior other than for physically demanding tasks (Borg, 1978) or for those that involve apprehension (Spyker et al, 1971), due to idiosyncracies among subjects (Jex & Clement, 1979). For relatively low workload, low stress simulated flight, heart rate was found to reflect variations in physical control demands (Connor & Wierwille, 1983), but not the cognitive aspects of siumulated flight (Casali & Wierwille, 1982; 1983; Rahimi & Wierwille, 1982). For operational tasks, such as flying, the typical finding has been that heart rate increases upon takeoff and landing, but only if pilots are responsible for flying the aircraft (Hart, Hauser, & Lester, 1984; Roscoe, 1978; 1982; Ruffle-Smith, 1979). If the aircraft was flown by another pilot, then heart rate was insensitive to workload variations. Since the pilot-not-flying was still an occupant in the aircraft under the latter circumstances, it sugests that apprehension or fear is not the cause of variations found for the pilot responsible for flying the aircraft. Rather, maintaining a level of preparedness appropriate for the degree of responsibility seems to be the key factor. Such an elevated arousal level may result in high heart rates in anticipation of maneuvers and inadequate performance may occur if it is absent (Roscoe, 1982). Thus, heart rate may provide information about the state of the operator, but it may not relate to "workload" per se. In summary, heart rate is an easy measure to obtain, and may reflect some information about the state of an operator, but it may not be sensitive to variations in cognitive workload, particularly in situations where responsibility and stress do not have a role in workload.

Heart rate variability. Although heart rate may be affected by so many subtle psychological and physiological processes that it is not a useful workload measure, heart rate variability (or sinus arrythmia), has been found to be relatively sensitive. Even though many statistical procedures have been used, the common finding is that heartbeat irregularity in a resting subject is suppressed as the difficulty of a task, particularly a mentally demanding task, is increased. An entire issue of Ergonomics (1973, 16, 1-112) was devoted to this measure, suggesting the widespread interest in it. Even though it has been found to be sensitive across a wide range of tasks and load levels (summarized in O'Donnell, 1979; Wierwille & Williges, 1978), no sensitivity has been found for others (Gaume & White, 1975; Hicks & Wierwille, 1980; Casali & Wierwille, 1982;

1983). This seems to be the most promising measure of cardiac functioning, however, even it does not reflect workload in all cases.

The 0.1 Hz region of the spectral analysis of the beat-to-beat interval has been related to the amount of controlled information processing (Mulder, 1979). Variations in power in the 0.1 Hz region are thought to reflect mental workload, decreasing as workload is increased. Since variability in this region contributes significantly to heart rate variability, it should reflect similar processes indirectly.

Blood pressure. Blood pressure may increase with the stress that may accompany workload, however it may not relate to variations in worklod in the absence of increased stress. In addition, practical problems limit its utility as a workload metric. Although it is a relatively easy measure to obtain, and can be automated, it cannot be recorded continuously and repeated cuff inflations causes discomfort. Finally, blood pressure reactivity to environmental and task stressors may not covary with other measures of cardiac functioning and differs among individuals. For example, it has been found that "type A" individuals (with otherwise normal blood pressure levels) exhibit momentary increases in blood pressure in response to frustration, failure, and time pressure, while "type B' individuals do not (Chesney & Rosenman, 1983)). This finding suggests an interesting application of physiological measures to characterize individual operators' responses to different situations.

Respiration. There is some indication that breathing patterns reflect workload, becoming more shallow, regular, and rapid (Wierwille & Williges, 1978). For example, Spyker et al (1971) found that the volume and frequency of breathing were correlated with subjective workload assessments. However, others have found no such correlation (Gaume & White, 1975; Casali & Wierwille, 1983). A high correlation between heart rate and respiration rate is often reported, reflecting the physical demands of a task. It has been suggested that components of heart rate and blood pressure related to respiration can be statistically removed in the frequency domain between 0.2 and 0.4 Hz.

Galvanic skin response

Galvanic skin response (GSR) is a term used to describe the resistance of the skin to the flow of mild electrical current between two electrodes. Emotional reactions to different situations may alter the moisture content of the skin, thereby changing its conductance. This technique has been used for years as a "lie detector" test in law enforcement, however its direct application to workload assessment may be somewhat limited. This measure, like so many other physiological techniques, reflects primarily the level of activation or arousal of the operator, rather than components of workload associated with imposed demands or operator behavior. In addition, it requires many replications for ensemble averaging, there are large individual differences in reactivity, and it responds relatively slowly to changes in the environment (O'Donnell, 1979).

Measures of eye function

Because so much information presented to operators of modern systems is presented visually, an operator may consciously or unconsciously control the flow of information through blinking, direction of gaze, and focal length. Thus, monitoring changes in these parameters might provide useful indications of visual workload. In addition, eyes are not only a major channel through which information is received, but also may serve as a source of information about the internal state of an operator (O'Donnell, 1979).

Pupil diameter. Variations in pupil size have been found to reflect variations in mental workload with a relatively high degree of reliability. Pupil size has been related to problem difficulty, the effort involved in finding a solution, and short term memory requirements in several studies (Beatty, 1979; Casali & Wierwille, 1983; Kahneman & Beatty, 1967). Size changes occur rapidly from the onset of stimuli, suggesting that this measure may be used to evaluate moment-to-moment variations in workload. In addition, it is possible to obtain and analyze pupil size information precisely and automatically and this information is often available coincidentally when eye movements are monitored, The major advantage of this measure is its sensitivity to workload differences among different tasks as well as to more subtle differences within a task. Its major drawback is its responsiveness to factors other than workload (e.g. eye movements and blinks, change in ambient lighting, and emotions), however it shows promise for workload evaluation in environments where there are suitable recording devices and lighting can be controlled.

Eye blinks. It has been suggested that blink rate is inversely related to mental workload (see, for example, Holland and Tarlow, 1972). More recently, both timing and duration of eyeblinks as well as frequency have been found to reflect workload-related phenomena in simulated flight (Stern & Skelly, 1984). Shorter durations were found for the pilot-in-command than for the copilot and for high-workload weapons-delivery and threat-avoidance flight segments. Longer duration eyeblinks were found as time-on-task increased, suggesting that fatigue as well as workload are relevant. Blinking was inhibited while information was being obtained and tended to occur after decisions had been made, suggesting the possible use of this measure to assess information processing activity.

Direction of gaze. The primary reason this measure is used in applied settings has been to determine what instruments, displays, and information sources were used by operators as well as the pattern of fixations. Operators selectively invest more time and attention in some sources of information than others. The shifts in eye fixation may reflect conscious, active attempts to seek required information to accomplish a task, a learned, automatic scan pattern, or an unfocused glance while information from another sensory modality is processed. Measurement techniques range from video cameras, placement of electrodes around the eye, to oculometers in which one or more infrared light sources are reflected off the cornea to a recorded image of the visual field. Although oculometers provide the most precision and automated data recording and scoring, they are expensive and require restriction of operator head movements (unless they are helmet-mounted). Some typical findings will be described below, although the range of applications is much greater than this cursory review suggests. The amount of visual free time has been evaluated as an indirect measure of concurrent task workload (Harris, et al, 1982; Sanders, et al, 1977; Strother, 1973). For this measure, the time spent looking as a side task reflects the visual monitoring and processing resources available after performance of a primary task. The degree to which an operator's direction of gaze leads (or lags behind) movement of a target can be monitored as an indicator of the difficulty of the movement trajectory being tracked (Hartzell, 1976). Fixation durations have been found to decrease as workload is increased in simulated and actual flight (in Gerathewohl, et al, 1978). Workload-related changes in scan patterns may occur to eliminate nonessential sources of information under conditions of high loading (Spicuzza et al, 1974). Thus, eye movement patterns and transition probabilities may reflect changes associated with variations in workload and training level (Stephens et al, 1980).

Although information about where an operator is looking, and for how long, may be useful, there are many pragmatic problems associated with implementation and interpretation, and the relationships among dwell time, scan patterns, and workload are not straightforward. For example, information is processed from the periphery of the field of view as well as from the center and not all information within the fovea is processed. Individuals may choose to concentrate on any number of different aspects of a visual stimulus (e.g., color, shape, meaning, location, etc) and it is impossible to determine which aspect(s) are being processed from the direction of gaze. Finally, the measurement equipment is often uncomfortable and may limit range of movement, reducing the utility of this measure in an operational environment.

Electrophysiological Techniques

The measurement of electrical activity of the brain has been studied as an objective index of workload because of the obvious connection between the brain and behavior. The occurrence of specific sensory events has been related to predictable patterns of electrical activity in specific parts of the brain recorded by scalp electrodes; the event related potential (ERP). Unlike the raw electroencephalogram (EEG), which has been difficult to associate with information reception or processing, the ERP "signal" can be detected in the "noise" of the ongoing brain activity by statistically averaging several occurrences of similar events, since the electrical activity of the brain evoked by one event tends to follow the same course. A typical finding would be that the latency and amplitude of "early " components of the electrical activity that follows the occurrence of information (within 200 msec) increase as a function of processing required to encode the information. Cognitive processing workload has been associated with the amplitude and latency of the "late" positive component that occurs between 300 and 500 msec after the onset of a stimulus. If the ERP is elicited by information required for a secondary task, its amplitude is decreased as the workload of the primary task is increased. This sensitivity to workload variations across stimulus sensory modalities covaries with secondary task performance measures of workload (Israel, et al, 1980). More recently (Kramer, Wickens, & Donchin, 1984), ERP amplitudes obtained with a secondary task paradigm reflected the degree to which elements of the "secondary" task are also required for "primary" task performance. Lower priority, truly "secondary" task attributes which do not become integrated with a primary task have the lowest processing priority and are associated with the lowest amplitude late component of the ERPs.

Another commonly used technique for measuring workload-related electrical brain activity is the steady state evoked potential. With this method, a stimulus is presented at least eight times per second and EEG activity during the presentation of each stimulus event is recorded. The amplitude and phase angle of the resulting ERPs provide a stable measure of relatively small changes in the environment (Wilson, 1981; Wilson & O'Donnell, 1982).

Neurophysiological recordings provide the only direct measure of information processing activities. In addition, surface scalp electrodes rarely interfere with performance. Evoked potential measures are complex, providing multiple sources of information. Different electrode locations on the scalp and the latencies and amplitudes of different aspects of the waveform are responsive to different stimulus properties and decision-making activities. Finally, because these electrical signals are evoked by discrete and experimentally controllable events, neurological events can be pinpointed with temporal precision, reflecting fluctuations in task demands or the effect of combining primary and secondary tasks. It is less easy to interpret the information than it is to obtain it, however, and it may be difficult to identify responses to discrete events in the midst of ongoing activity in a realistically complex task. Steady state and evoked potential measures are expensive to obtain and require specialized hardware, extensive data storage and reduction, and electrically "clean" environments. Finally, they are subject to many artifacts (e.g., eye movements or eye blinks) which might themselves be associated with the level of workload.

Analytic Methods to Assess and Predict Workload

A comprehensive model of man-machine systems in which behavior and performance is described and predicted in terms of costs and benefits is the ultimate goal of workload assessment technology. The designation "model" may be applied relatively loosely to include dynamic, mathematical equations used to predict human behavior and performance as well as descriptive flow diagrams, networks, and computer simulations of complex systems. The critical test for any analytic tool is its ability to predict future performance from current information without the need for empirical investigation or costly cut and try methods. Most available paper and pencil or computerized models were developed to predict system and operator performance and only address workload as a model parameter. However, these models can be useful for reducing and interpolating empirical phenomena so as to explain complex and interactive relationships among task demands, system behavior, performance, and operator experience. They usually include both system parameters (e.g., vehicle dynamics) and operator parameters (e.g., muscular lag). They may offer insight into human behavior by manipulation and control of relevant model parameters through an unstructured correlational approach (with no reflection of cause and effect) or a structured one in which elements represent the relationship between specific input and output variables. Workload estimation is accompished by examining the values assumed by relevant model parameters in order to achieve the best fit between predicted and obtained data in the development phase. If parameters that reflect human information processing structures and limitations in addition to psychomotor factors can be identified and incorporated into model structures and if the focus of the models can be expanded to include discrete, infrequent, supervisory control functions in addition to continuous closed-loop control, then substantially greater benefit might be derived from modelling efforts in terms of workload prediction and assessment. As there are several excellent reviews of the use of analytic techniques for the measurement of workload, (Parks, 1979; Phatek, 1983; Poston, 1978; Soulsby, 1983), the following overview will be brief.

Task description is the mandatory starting point for any modelling process, however, the form of the description and the role assigned to the human operator depends on the model structure. Quantitative values are determined either theoretically or empirically. The resulting structure can be applied to the set of tasks for which data do exist and can be extended to other situations if the underlying theory permits. Before discussing any specific modeling approaches, some basic issues related to the combination of even the simplest of subtasks into a complex task might be considered. Few tasks characteristic of modern systems require the continuous inner-loop control that was the focus of early man-machine models. Rather, most involve a series of discrete, short-term, maneuvers and segments (Heffley, 1983) that may interact and overlap in time and function. Operator workload may vary greatly depending on how operators organize their actions and execute the subtasks. Considerable information exists about the performance of many critical task elements, and global measures of performance and operator opinions can be obtained about the completion of complex missions. The need, then, is to determine the rules by which estimates of subtask workload, performance, and completion time can be combined to predict the workload or performance of operationally complex missions with new or existing equipment and procedures under a realistic range of circumstances.

For many tasks, subtask workloads may be combined by a simple additive function with a small cost (defined as increased workload or performance deficits) for concurrence. This function was found, for example, when individual laboratory tasks (e.g. single- and dual-axis tracking, memory search, dichotic listening, etc.) were combined spatially and temporally, but were not integrated functionally (Gopher & Braune, 1983). Overall task load may be equal to the sum of component levels plus a significant concurrence cost for activities that compete for common, limited resources. The joint performance of subtasks that each independently require the same limited resources will impose more workload than would be predicted by simply combining single task levels. Performance decrements on some or all of the component subtasks may be significant, and additional time will be required to switch among the competing tasks. Resources may be shifted from one task to another (if they share structural properties and require some common, limited resource), with a consequent change in performance and workload (Broadbent, 1982; Navon & Gopher, 1979; Norman & Bobrow, 1976). If they do not, then shifting priorities or changing the difficulty of one task will have little influence on performance of another, structurally unrelated task. Other rules for combining component tasks loads have been found, as well. For example, Hart, Sellers and Guthart (1984) and Kantowitz, et al, (1984) selected laboratory tasks (target acquisition and memory search) and components of simulated aircraft control (e.g. heading, altitude, speed, etc) that could be functionally integrated and shared common elements. It was found that groups of tasks were performed considerably more quickly and with less workload than might be predicted from combining single task levels.

The sources of workload may shift from one mission segment to another. For example, vehicle characteristics and information rates may drive the level of workload at some points, whereas inadequate time to complete urgent tasks or a perception of risk may be more salient at other times. Thus, concepts of effort, difficulty and capacity limits must be applied carefully when estimating the load that will be imposed by subtask combinations in complex systems. If information is well integrated (in sensory terms) or if the same response serves to complete several subtasks, multiple tasks can be performed concurrently with little decrement in performance, and little increase in workload over the single task level. In addition, since complex systems require the performance of many discrete, short-term, subtasks, the way that subtasks fit together temporally becomes a critical factor in estimating overall workload. It is clear that the time required to complete subtasks is not, by itself, sufficient to predict the workload that the task will impose under different circumstances or when it is performed in combination with other activities.

Time Line Analysis

The simplest model structure is a time line analysis in which execution times and schedules of all task elements are enumerated. Workload is defined as time pressure and is quantified by computing the ratio between the time required for task performance and the time available. When this ratio is one, the operator is constantly occupied by some aspect of the task and has reached his workload capacity limit. Some approaches allow for loadings that exceed this value, acknowledging the possibility that operators can accomplish concurrent tasks within the same period of time.

The Workload Assessment Model (WAM) of the Computer-aided Function Allocation and Evaluation System (CAFES) developed at the Naval Air Development Center is one example of such an approach, although the formulation of a time line for hardware use or mission conduct is performed almost universally in any complex system development process. The Systems Analysis of Integrated Networks of Tasks (SAINT) is another such model (Seifert, & Chubb, 1978). It is a simulation model comprised of a collection of sequential, dynamic, submodels represented in a network. The fundamental elements are tasks, required resources, relationships among tasks, and system status variables implemented in a symbolic computer language. It operates by searching for the optimal path through the network. Simulation models such as SAINT and the Human Operator Simulation (HOS) model (Lane, et al, 1980), which focus on the management of cockpit information, allow the prediction of system workload and performance with a computer-based analysis program. The utility of this approach depends on the fidelity of the assumptions and algorithms used to describe operator behavior and the completeness of the subtasks included. Workload and performance are predicted (and later measured) by combining information about the component subtasks. These models are based on two primary assumptions: (1) the human operator is a single channel processor who generally does one thing at a time; and (2) the time available to do a task in sequence with other tasks is inversely related to workload. Each additional increment in task demand is assumed to require an increase in effort until the capacity of the operator is exceeded. A strictly additive single-capacity model predicts that a given task should add a constant amount of workload to any ongoing activity and the amount can be predicted from single task levels.

Analytic Models

Analytic models reduce the problem of operator modeling to one of defining relevant pilot inputs and system outputs and the mapping between them. Unstructured models treat the human element as a "black box", relating inputs and outputs so as to achieve the best fit between empirical data and the output of the model, without concern for the underlying human information processing structures. The describing function model is one example of an unstructured model. It depicts the human operator as a quasi-linear servomechanism in the frequency domain (McRuer & Jex, 1967). The classical formulation equates workload with the amount of lead generation and gain required of the operator to compensate for system perturbations. The portion of the human response that is unrelated to the vehicle forcing function is termed "remnant". The "Paper Pilot" model (Anderson, 1970) makes explicit the goal of all modeling efforts -- that of matching the predictions and descriptions of workload to the subjective opinions provided by human operators. This approach assumes that human operators select whatever strategy will result in the lowest level of rated workload. and that performance and workload will have a reciprocal relationship with respect to pilot opinions (Phatek, 1983). Because both workload and performance are assumed to be the weighted sum of many components, and because their effects are assumed to be additive, any number of possible variations in performance and workload can predict the same rating of workload. This eliminates the possiblity of a unique (and therefore diagnostic) solution. Unstructured models provide a useful method for analyzing closed-loop manual control tasks in which the human operator may in fact act as steady-state, linear, controller. Because the model parameters are not based on the capacities or structures of the human information processing system and the underlying rules of thumb may predict machine load more accurately than the behavior and experience of a human, this type of model has limited utility for workload quantification or prediction.

Structured models

The optimal control model, which was originally proposed for continuous manual control, characterize the human operator as an optimal state estimator and controller. It is a normative model that describes what a well-trained, highly motivated human operators should do to compensate for system perturbations and their own internal limitations. Workload is related to the effort required to improve an inadequate internal model of the system, relating directly to the signal/noise ratio of the system controlled. Within this framework, workload has been defined as the fraction of an operator's capacity required to perform a given task (Levison, Elkind, & Ward, 1971). Again, pilot opinion ratings are universally used to "validate" the success of the model in describing and predicting operator workload. Specific model parameters are related to different aspects of human behavior. This has an obvious advantage for workload assessment, because there is some degree of isomorphism between model parameters and human perceptual, cognitive and motor capabilities, but there is still no guarrantee that any set of model parameters uniquely describes the obtained data (Phatek, 1983; Phatek et al, 1976). The model is not parsimonious in representing the response behavior of human operators, and its validation still depends on subjective ratings.

Decision models focus on the operator's sampling of information from different displays to make dynamic decisions about scheduling tasks. Workload is assumed to relate to uncertainty, time pressure, switching from one task to another, and planning. In information theory models, definitions of task demands and predicted performance have been derived from conditional probabilities and workload imposed by different activities estimated by the fraction of the operator's attention. Supervisory control models focus on such task features as scheduling of individual task elements or groups of elements, subtask priority, payoffs, and difficulty, and the number and rate of individual tasks to be performed. Abstract simulations of process control tasks have been used to determine task parameters that are influential in creating different workload experiences with a supervisory control task (Hart, Battiste, & Lester, 1984; Tulga, 1978).

Petri nets, which are abstract, formal representations of the flow of information and control through a system, have been proposed as a framework within which to quantify and predict the workload associated with complex man-machine tasks (Madni & Lyman, 1983). "Places" are static or dynamic activities. They are equated with human-related processes and activities. Passive activities are associated with the least load, whereas skill-based, rule-based, and knowledge-based dynamic activities (Rasmussen, 1983) are associated with increasing levels of workload. "Transitions" from one activity to another are characterized by Boolean expressions involving the normal completion of internal events (low workload) or the occurrence of an expected (moderate workload) or unexpected (high workload) external stimuli or conditions. Although this approach to workload prediction has yet to be applied to an operational system, it shows promise as a structure for relating different types of imposed workloads to different levels of operator behavior and experiences. As with other models, the success of a Petri net in predicting workload is validated, and in fact iteratively created, by eliciting information from skilled operators.

Expert systems have been used to assess and predict human operator workload in complex systems. For example, the Crew and Aircraft Sub-Systems Model for the Management of Aircraft Equipment (MESSAGE) was developed and applied to the transfer of information and flight path control in transport aircraft manufactured by Airbus Industrie (Boy & Tessier, 1983). Unlike earlier pilot models, MESSAGE was developed explicitly to assess aircrew workload. It can perform a static taskload analysis as well as a dynamic, interactive workload estimation for a specific mission. It contains human operator, cockpit, and air traffic control models designed to evaluate system and procedures design alternatives based on their workload impact. Such values as ease of operation and monitoring, accessibility, and visibility of cockpit features are calculated as a function of the time required. The human operator is characterized as an information processing system with a memory, processor, receptors, and effectors having three basic functions: data acquisition, planning and execution. Due to the explicit mapping of human operator variables into model parameters, MESSAGE can provide diagnostic information about the nature and magnitude of specific transitory or enduring sources of workload.

Heuristic models

Heuristic models describe and predict human operator behavior by referring to rules-of-thumb. They focus on the probability that an operator will be prompted to take corrective action given the current state of the system controlled. This approach is dynamic and can be used to describe discrete, discontinuous, supervisory tasks as well as continuous, closed-loop control tasks. Because it is based on probabilistic criteria, it can explain why different operators, faced with the same task, may respond differently and experience different levels of workload.

One heuristic approach applies fuzzy set mathematics to the description of human operator performance and workload. It is assumed that the behavior and strategies of human operators is based on their perceptions and decision rules derived from past experiences. Fuzzy set theory provides a mathematical means of formalizing the imprecisely formulated linguistic descriptions of decision making processes and experiences whereby different levels of workload are experienced. However, the utility of this approach depends on the completness and appropriateness of the heuristics and the abilities of skilled operators to express their own behaviors, decision processes, and experiences systematically and precisely . In one application of this technique to the measurement of workload (Moray, 1983), it was assumed that different individuals may attribute different importance to the influence of specific variables (e.g., task difficulty, stress, and time pressure). Thus, an experience of "rather heavy workload" may be created by different combinations of dimensions from one subject to the next, although there are extreme combination that elicit agreement from everyone. Variations in associations among experienced workload, task performance, and objective and physiological measures of workload can be mathematically accomodated using this approach.

Advantages and disadvantages

During system design, time line analyses or other types of models are the only techniques available to predict the workload that will be imposed by the completed system. They may identify conflicts for limited resources, periods of momentary overload in advance of system construction and quantify the workload impact of design alternatives. The quality of the information is as good as the structure of the model and the values selected or computed as model parameters. An unintentional contribution to the analysis of workload provided by the process of modeling is the requirement imposed on the modeler to operationally define system goals, task demands, operator behaviors, and relevant performance indicators. This alone improves the possibility of accomplishing a useful workload analysis or prediction, regardless of the measurement techniques used subsequently. In short, the act of modeling causes the analyst to think logically and provides a framework for thought processes and available data.

Unfortunately, these apparently objective analytic techniques, used to quantifying and predict the workload imposed on an operator and the response of the system to such demands, ultimately reflect upon the subjective experiences of test pilots and experimental subjects used during development and validation. Furthermore, many models of operator behavior were developed for aerospace applications. In many cases, Cooper-Harper ratings of aircraft handling qualities have been used to validate model-based predictions about workload (Hess, 1977). Although vehicle handling characteristics are related to the level of imposed workload, many other system- and operator-related parameters are equally important to the level of load experienced by an operator.

The value of models for predicting performance in situations that do not yet exist is limited by the abilities of the human designers and operators to project themselves into situations that they have not yet experienced. Validation with converging workload assessment techniques is necessary to supplement the ubiquitious subjective ratings now employed in order for them to have value for predicting and assessing the workload of complex man-machine systems. Neither paper-and-pencil not computerized models can provide any more than a conceptual framework for thinking about workload-related problems if their predictions have not been tested against operational problems that have been quantified independently. Models are costly and complex, yet they rarely provide more than a formalized subjective approximation. They must necessarily focus on overt behavior, limiting their utility in supervisory control and highly automated situations. Finally, most make unrealistic assumptions about the motives, skills, and attention-allocation and prioritization policies that are not representative of human operator behavior. Particularly for unstructured models, the lack of isomorphism between model parameters and human information processing and responding structures restrict their diagnostic powers, and the lack of unique mathematical solutions weaken their utility even further.

APPLICATION OF WORKLOAD ASSESSMENT TECHNIQUES

Workload is a complex subject that means different things under different circumstances for different people. It may be relevant for a variety of reasons, and it may be assessed or predicted with varying degrees of success using a wide range of techniques. Workload questions vary widely in scope and focus, thus a precise formulation of the question to be answered by an analysis, prediction, or modification effort is crucial. Some workload questions may relate primarily to the structure and organization of the task itself or the range of environments in which it may be performed. Yet others focus on the effort or emotional cost to the operator of performing the task. For example, the question, "Can the operator do more?" might be addressed by a different analytic approach than the question "What is the cost to the operator of doing more" or "Will the workload of this task change under weightless conditions?". The task requirements, structure, and resources may be identical in each case, however the measurement technique that will answer each different question will differ. Furthermore, the information given by each measurement technique reflects a slightly different aspect of the task and an operator's experience with it. In addition, the existence of an operational system with which to perform empirical testing may shape the questions that can be answered and the measurement techniques that can be used. Some questions may not relate to workload at all. Instead, they should be considered as equipment design problems, matters related to excessive stress or fatigue, or labor/management issues, without even invoking the issue of workload.

Many workload-related analyses involve predicting the effect of proposed systems on the workload and performance of operators. Questions might relate to the physical design of the hardware, the level of automation required, operator selection and training, the range of missions that might be accomplished, and research or required (but unavailable) technology that is needed. The level of uncertainty inherent in such analyses varies directly as a function of the degree of similarity between the proposed system and existing systems for which empirical estimates of workload and performance have been obtained or the degree to which subtask functions can be identified and evaluated analytically. Since the system does not yet exist for experimental assessment, analytic techniques and subjective predictions are the primary assessment tools. The predictions must necessarily focus on imposed workload and hardware characteristics. Task goals, such as requirements for speed an accuracy, the temporal structure and intensity and complexity of task demands, system resources, environmental variables, and the knowledge base and training level required of potential operators may be included in a task analysis or computer simulation. In addition, system response characteristics may be included with estimates of operator response characteristics based on general models of human behavior. It is relatively more difficult to predict the perceptions, strategies, errors, and subjective reactions of the operators, however, particularly if system is significantly different than existing counterparts.

A wide range of questions might be posed about existing systems. For example, momentary periods of extreme workload or prolonged intervals of moderate workload might be identified as a predisposing condition for an operator error or as the direct cause of an incident or accident. This might prompt a re-evaluation of current procedures or system design to reduce or modify unacceptable load levels. Less pressing questions might be prompted by the need to select among alternative control or display configurations to upgrade an existing system. Finally, questions related to the health and job satisfaction of operators might require an evaluation of crew workload. With an existing system, there is the possibility that alternative configurations or solutions can be compared empirically and a wide variety of measurement techniques may be considered (e.g., subjective ratings, primary or secondary task performance measures, modeling or task analysis, and physiological recordings). The selection of a measure should be based on the specific focus of the research question (e. g. imposed workload, operator behavior, system performance, or the impact of task performance on an operator) and practical constraints imposed by the research setting. If an empirical analysis is performed in an operational environment, then relatively gross measures of primary task performance (e.g., whether or not the missions was completed), imbedded secondary task measures that occur naturally within the task environment, on-line observer ratings, and post-hoc operator ratings might be the only alternatives possible. Although measures of cardiac functioning may be less directly related to operator workload than electrophysiological measures of cortical activity or recordings of pupil diameter and eye-point-of-regard, they may the only physiological measures that can be introduced into an operational setting. Furthermore, the lack of experimental control typical of operational environments and the requirement for electronically "clean" conditions, precise presentation of eliciting stimuli, millisecond accuracy in data recording, and high volume data storage may limit the use of many physiological measures and primary and secondary task performance indices.

The most common situation is one in which similar existing systems or preliminary versions of proposed systems exist as full-mission or part-task simulations. These part-task versions of existing or proposed systems may vary widely with respect to the cosmetic and functional accuracy with which they represent the target system. Furthermore, the performance and workload estimates obtained for component tasks may or may not accurately reflect their contribution to overall task workload when they are presented as part of an operational system. For example, one controller might create significantly more workload than another in a laboratory task or one display configuration might result in significantly longer response latencies. However, the amount of workload contributed by even the worst of these alternatives to overall system workload might be so limited that it would be irrelevant. Nevertheless, part-task and full-mission simulations do permit empirical testing, validation of predictions about specific model parameters, experimental control over specific variables, and the application of a wide range of individual and converging measurement techniques. The most important concern in part-task research is that aspects of the target task that are relevant to the research questions are included and simulated with sufficient realism. If this can be accomplished, then performance measures for secondary as well as imbedded tasks that are relevant for measuring operator strategies, behaviors, and success in meeting performance criteria can be recorded, subjective ratings obtained, and a wide range of physiological measures collected.

There are so many potential measures with which to predict or assess workload that it may be helpful to group them according to the task elements for which they are sensitive. Some are appropriate for predicting task demands (e.g., time line analysis, mathematical models, secondary task performance), the behavior of the system (e.g., direction of gaze, reaction time, number and accuracy of responses, ratings by observers), or the operator's response to the task (e.g., subjective ratings, heart rate and variability, pupil diameter, electrophysiological measures). Within each classification, specific measures relate to different task elements. In addition, different combinations of contributing factors create the unique workload situation characteristic of any task. A difficult task may impose high workload levels because great precision is required, subtask rates exceed the response capabilities of a typical operator, information is complex, there is mechanical interference, or the environment in which it is performed is debilitating. For another task, the significant contributors to task workload might be the emotional stress imposed on an operator or the lack of sufficient training. For example, shuttle re-entry workload may be predicted with great accuracy (if it is performed by a trained astronaut), whereas exactly the same task requirements, performed by a truck driver without benefit of a two-year training program, may result in extreme workload. Thus, some assumptions must be made about the probable sources of workload in a given task as well as the research questions to allow the selection of sufficiently sensitive measures.

Few measures can address one aspect of workload without any influence from other variables, however. For example, it is difficult to quantify the objective difficulty of a task using subjective ratings provided by operators or measures of performance without some influences by operator strategies, perceptions, capabilities, expectations, incidental variables, and effort. On the other hand, operator variables (such as stress, fatigue, effort) are difficult to separate from task goals, difficulty levels, available resources, and environment. Different assessment techniques focus more on some aspects than others, but few can exclude the influence of other factors. Workload assessment might be like peeling back the layers of an onion. Each layer is as much an "onion" as any other layer, even though each has a different appearance and size and some layers are more accessible than others. Nonetheless, there is some basic essence of "onion-ness" that relates them all. On the other hand, there may be no "essence of workload". Rather, there may be a collection of dimensions, modifiers, levels, and components that combine to create various types of workload. The important issue, then, is to select measures that address the specific goals of the workload analysis that are sensitive to the predominant sources of loading in the target situation and are appropriately precise. Too much precision may be as useless as too little. An analysis that is too fine-grained may be insensitive to the overal complexity of an operational task, whereas one that is too crude with not be sufficiently sensitive. For example, continuous measurement of control activity, even if it is obtained with millisecond accuracy, may be irrelevant to understanding the information processing workload of a complex flight task, whereas, a single numerical rating of the workload experienced during each of several flight segments may have no diagnostic value and average across so many different contributing factors as to be meaningless.

Although it is important to resist the temptation to select a measure simply because it is available or in vogue, practical constraints are a fact of life. Thus, a balance between the scientific desirability of a measure and its operational practicality it required. The important point is to recognize the tradeoff that has been made and interpret the data accordingly. An elegant model structure provides no better information than a rule-of-thumb guess by a trained observer if it has not been validated, and thousands of data points obtained from a scalp electrode may provide no more information about operator behavior a simple frequency count of responses if stimulus presentation cannot be controlled. Finally, a specific description of what analyses were performed and what task elements were of interest may avoid a host of problems. Rather than calling every analysis "workload assessment", it might more accurate, useful, and diagnostic to refer to estimates of response frequency, intensity of effort, information complexity, emotional stress, success in meeting task goals, errors, or subjective experiences. Whereas each may relate to a single entity (e.g., workload), there is so little agreement about what that entity might be that precise definition and focus may provide not only more practically useful results, but contribute significantly to a theoretical understanding of the construct of workload itself.

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ANNEX R-XIII

PILOT WORKLOAD, PERFORMANCE, AND AIRCRAFT CONTROL AUTOMATION

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Annex XIII to Appendix R

PILOT WORKLOAD, PERFORMANCE, AND AIRCRAFT CONTROL AUTOMATION

R-XIII-1. The paper, "Pilot Workload, Performance, and Aircraft Control Automation" is reproduced on the following pages. The paper was presented at the AGARD symposium on Human Factors Considerations in High Performance Aircraft. The symposium was conducted at Williamsburg, VA during April 1984. The report was authored by Sandra G. Hart of NASA-Ames Research Center and Thomas B. Sheridan of the Massachusetts Institute of Technology.

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PILOT WORKLOAD, PERFORMANCE, AND AIRCRAFT CONTROL AUTOMATION

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SUMMARY

This report reviews conceptual and practical issues associated with the design, operation, and performance of advanced systems and the impact of such systems on the human operators. The development of highly automated systems has been driven by the availability of new technology and the requirement that operators safely and economically perform more and more activities in increasingly difficult and hostile environments. It has become obvious that the workload of the operators, particularly their mental workload, may become a major area of concern in future design considerations. There has been, however, little research to determine how automation and workload relate to each other, although it is assumed that the abstract, supervisory, or management roles that are assumed by operators of highly automated systems will impose increased mental workload. The relationship between performance and workload, which is poorly understood at best for relatively simple tasks, will be discussed in relation to highly complex and automated environments.

PREFACE

The goal of this report is to define and relate two critical issues in systems design and operation; automation and workload. It is clear from reviewing the rationale behind the introduction of automation into modern systems that a principal driving force has been the desire to enhance system capabilities while maintaining operator workload at acceptable levels. As more and more physical control activities have been successfully automated, to be replaced by "mental" activities on the part of the human operators, there has been a growing concern about the problem of mental workload and the need to redefine the human's role in automated systems. Thus, the topic of this paper is the relationships among different levels of automation and different kinds of workload and the intelligent allocation of functions between man and machine.

In the past, discussions of automation, like discussions of workload, have failed to provide practical or theoretically sound conclusions. They are terms that everyone uses, as though there is a shared understanding of their meaning. Yet, they are each such complex concepts that no one definition has been universally accepted for either one; definitions have lacked either precision or failed to satisfy a sufficient number of individual "definitions". Thus, the first section of this report will deal with definitions of automation, its function and purpose, benefits and liabilities. The next section will review traditional approaches to the definition and assessment of workload and propose a conceptual framework for subsequent discussions. The relationships among different aspects of workload and different forms of automation will be reviewed in the next section and the allocation of functions between man and machine in advanced systems will be considered in the final section.

DEFINITION OF AUTOMATION

As the micro chip invades our lives, computer-based automation has become an ubiquitous element in the private and professional lives of more and more people. Automation is a generic term for replacing human actions by human decisions executed by machines and for accomplishing clusters of related tasks by simple, executive commands. As the degree to which humans directly "do" tasks has diminished, the interaction between humans and machines has become increasingly indirect separated by intervening computer-based systems that control the execution of actions initiated by the operator. The term "automation" has been applied to functions as diverse as the control of a single quantity by a simple on/off mechanism, the concurrent display of information from several sources for human interpretation, and the control of complex processes in which automated systems replace certain human intellectual functions (Ref. 1).

For this discussion, the term "automation" will be applied to any use of a computer (or other machine) to perform tasks that might otherwise be performed by a human. It is the process by which essential functions are performed with partial, intermittent, or no intervention by an operator (Ref. 1) The level and type of automation may be described in terms of locus of control (whether a man or a machine provides the intelligence behind commands to a system), allocation of performance (whether a man or a machine actually executes a task), or the type of function automated (whether information is received, data stored, recalled or processed, control exerted, monitoring accomplished, and so on). In addition, the source of information, and whether it is managed, manipulated or accessed by the machine or the operator, or both, is another factor. Each of these dimensions may be associated with different allocations of responsibilities between men and machines depending on the design of a system, its mission, and the environment in which it operates.

Automation may be thought of as a continuum rather than as a discrete state. For example, with respect to decision making and control, (Ref. 2) there is a continuum between total human control, in which humans consider decision alternatives and then make and implement the decisions, and totally automatic control in which the system makes and implements decisions when it thinks it should and informs the human operator after the fact only if it thinks it necessary. Intermediate levels of automation between the two extremes in which men and machines share responsiblity and control might be:

1. The system suggests decision alternatives but the human may ignore them.
2. The system offers decision alternatives and the operator must select and implement from among them.
3. The system offers decision alternatives and then implements the one selected by the operator.
4. The system makes decisions but informs the operator in time for

human intervention before implementation.

5. The system makes and implements decisions, informing the operator after the fact either routinely or only if asked.

An operator's experience with a manual version of a system or its automated configuration, the distance between the operator and the system controlled, and the degree to which the operations and accomplishments of the automated system are known to the operator may determine whether automation is recognized, accepted, or used effectively. In addition, the proportion of functions accomplished by the operator or by the machine and the operator's ability to control an unautomated version of the system may be relevant factors as well. The length of time a piece of technology has existed may influence its inclusion in the set of things "automated"; the newer a feature, the more likely it is to be included. For example, most would consider cruise control in an automobile to be a form of automation. It is a relatively simple regulator available on newer cars, but it is an optional feature that many operators have not used. An automatic choke may or not be considered automation, depending on an operator's level of knowledge of automobiles. The function may occur without the knowledge or direction of a driver who has never adjusted a choke automatically, never recognizing it as a separate entity unless it malfunctions. Another driver experienced in the operation of manual chokes might appreciate (or bemoan) its presence, understand its operation, and monitor its action by the sound of the engine. Thus, an element of subjectivity may color the identification of a feature or system as automation. Yet another early requirement for automobile operation - - the manual adjustment of the spark advance - - is now universally accomplished automatically and has been for so many generations of drivers, that it has passed from being considered "automation" to being thought of as an integral element of the engine.

WHY AUTOMATE? AND WHY NOT?

Although there are many real benefits to be derived from automation, it may be a mixed blessing. The fact that it is technically feasible to automate a function is not a sufficient justification for doing so (Ref. 3). In some instances, the decision to automate some or all of the components of a man-machine system is based on a desire for increased safety or reliability by reducing the opportunity for human error. This might be accomplished by automating routine tasks that involve memorizing and monitoring or those with strict time constraints. The decision to automate may stem from a desire to avoid excessive workload (e.g. factors such as information overload or tasks that must be performed simultaneously). Automation may be provided to improve performance. This might be accomplished by assigning tasks that require precision or complex mathematical computations to machines or by providing operators with automatic warning of impending failures or emergencies. In addition, automation might increase human, and therefore system, capabilities by permitting activities that humans do not have the capacity to perform (Refs. 4, 5). Finally, there may be economic reasons for automation such as fuel efficiency, reduction in crew complement, more reliable scheduling (Ref. 3), and reducing reliance on extensive ground support (Ref. 5).

Some of the potential drawbacks of automation include a reduction in operator skills, system understanding, or job satisfaction, and limiting operators' abilities to respond in a timely way when the unexpected occurs. In addition, operator inactivity, complacency, as well as overall system cost might be increased by automation. Some problems might be avoided by applying automation more selectivity, allowing operators to choose among automatic and manual modes, and providing operators with additional training or meaningful activities to maintain their involvement with the system. Operators must value and trust the automated systems. If the machines are safe, efficient, and reliable, and if they are responsive in allowing operators to interact in natural ways and provide appropriate information about the state of the system, many potential problems might be avoided. Finally, humans should not be required to perform menial tasks that subordinate them to machines (Refs. 4, 5).

THEORIES AND DEFINITIONS OF WORKLOAD

The costs and benefits of task performance to the operator of a system results from the mission requirements that the designer of the task intended to satisfy that are modified by many factors stemming from the task, the environment, and the operator. One type of cost that results is the complex phenomenon termed "workload". Although this term has intuitive meaning for most, its precise and objective definition has eluded both scientific and engineering communities. To the extent that automation changes the goals, structure, or resources available for a task it may be expected to change the workload experienced by operators as well. As the tasks of interest have become less routine and as the computer has become a cooperative party in decision-making and control, the appropriate basis for defining workload has become even more elusive. This is particularly true when describing the transient workload occuring when a dull monitoring task suddenly becomes a frantic effort to assume control of a vehicle following a system failures or emergencies.

Automation is often introduced to reduce the physical workload of an activity, a goal that has been accomplished with great success. In other cases, it has been introduced to allow a reduced crew complement or to enable existing crew members to perform additional tasks. However, a concomitant of providing automated systems has been the introduction of substantially increased mental workload in place of the reduced physical workload, due, in part, to the added burden of supervising or monitoring the automation. This tradeoff between physical and mental workload has been inferred rather than proven, however, because mental processes are rarely available for direct measurement or quantification. Computers may soon accomplish such a large proportion of the direct control of most systems that operators will become supervisors, decision making will replace controlling, passive monitoring will replace closed-loop integration, and theoretical, high-level system knowledge will replace mechanical understanding. Thus, there is increasing need to monitor, measure, define, and control whatever "mental workload" is to keep it within the capabilities of the human operator.

The cost to the system hardware of performing its part in a man-machine system might be termed "workload" as well, but this type of workload <u>can</u> be measured. For example, computer cycle time, bytes of memory required, processing capacity or fuel resources consumed, mechanical strain, exceedance of tolerance limits, and rate of throughput might serve as objective indicators of the load placed on a machine by performing a task. Although some intervening variables might affect this value (e.g. environment or maintenance) the machine is not free to perceive the task requirements in any way other than literally. Individual biases, different strategies, or variations in allocation of effort are not possible. Every response is overt and predetermined by the system architecture.

The precise definition and measurement of operator workload has been the topic of debate and research for decades. Each different theoretical or practical approach has devoted attention to different aspects of this complex construct. Many measures of workload have been developed without a theoretical foundation, thus, they cannot predict what might happen in a new situation and the phenomena observed under one set of circumstances cannot be extended to other circumstances with any degree of assurance. Unfortunately, many or most current techniques for developing workload measures are inherently circular. Because it is difficult to independently and objectively predict the workload that a task will impose, it is equally difficult to objectively validate candidate measures. If different task levels produce variation in the measure being validated, then the measure is thought to have "succeeded". If not, then it has "failed" and one is not able to determine whether the result occurred because the task demands were different than anticipated. Because there are no standardized tasks available by which to impose known levels of workload under specific environmental and situational constraints, there is no concrete anchor against which proposed measures or theories can be tested.

Research has shown excellent agreement among some measures of workload and among some manipulations of different task parameters but none in others (Ref. 6). Lack of agreement among different measures of workload may occur for a variety of reasons, not the least of which is that many commonly used measures are neither appropriate for nor sensitive to variation in workload. For those measures that are valid and reliable, however, the discrepancy may occur because different measures are selectively appropriate for different dimensions of the complex phenomenon of workload.

To many system designers and human factors engineers, workload is defined by the demands of a task - - literally the "work" that is "loaded" on an operator. This formulation has served as the explicit basis for task analytic approaches to the measurement of workload and as the implied foundation for other approaches. In the tradition of ergonomics, workload has been conceptualized as effort, particularly physical effort expended in an attempt to meet task demands. This earlier, physical focus required the measurement of overt actions by external consequence (e.g. buttons presses) or internal changes (e.g. muscular movement). The temporal component of workload has been emphasized by characterizing workload as "time pressure" (e.g. time required versus time available). The typical measures adopted for this approach have been time and motion studies and subjective ratings.

Various models of the human operator have been developed in which workload was varied as a model parameter or estimated in a predictive sense. For example, the optimal control model, which was originally proposed for continuous manual control, characterized the human operator as an optimal state estimator and controller. Workload was assumed to relate to the effort required to improve an inadequate internal model of the system. Decision models focused on the operator's sampling of information from different displays to make dynamic decisions about scheduling tasks. Workload was assumed to relate to uncertainty, time pressure, switching from one task to another, and planning. In information theory models, definitions of task demands and predicted performance have been derived from conditional probabilities and workload imposed by different activities estimated by the fraction of the operator's attention. Other researchers have conceived of workload in terms of physiological correlates of arousal and stress. They evaluated these factors by measuring physical changes in heart rate, respiration, muscle tension, and pupil size. The role of workload in operator job satisfaction, corporate/union negotiations, and interpersonnel relations has been studied with emphasis on the subjectively experienced levels of workload as reported by the operators.

More recently, workload definitions have focused on cognition and attention and have emphasized mental rather than physical workload. The shift in focus from measuring arousal and physical activity or quantifying task load purely in terms of overt actions has accompanied the introduction of automation into systems that were previously characterized by direct physical control. A typical conceptualization would involve the definition of workload in terms of the attention required by a task, or the additional capacity yet remaining to perform another task, with possible reference to the intensity of mental or physical effort exerted. A common paradigm employed within this framework is the dual-task or secondary-task paradigm in which an additional task is superimposed on a primary task. Objective performance on this task is evaluated as an estimate of how much reserve capacity is available after performing the primary task. Measures of the electrical brain activity that accompanies cognition under different levels of workload have been obtained by recording single trial, averaged, or steady state cortical evoked potential.

CONCEPTUAL FRAMEWORK FOR THE ANALYSIS OF WORKLOAD

In order to allocate responsibility for and control of system functions intelligently, measures of human workload must be developed which are equal in objectivity, reliability, and validity to measures of machine workload. Many ephemeral and unobservable variables are potentially involved. Thus, some form of organized framework is needed to relate the many factors that are, or have been thought to be, relevant in predicting, measuring, experiencing and defining human workload.

The structure and content for such a conceptual framework will be outlined in this section. It is not intended as a theory of workload, but rather as an organized, operationally defined description of relevant issues. The term "imposed workload" will be used to refer to the situation encountered by an operator of a man-machine system. It encompasses the task objectives and structure as conceived by the creator of the task, the environment in which it is to be performed, and incidental variables that might occur during any given performance of the task. However, it is the operator's perception of what is required that is the proximate driving force behind the strategies selected and the resources committed, rather than the conception of the task designer.

Performance, then, occurs as a consequence of effort exerted by operators to accomplish their perception of the task requirements. The level of performance achieved reflects the strategies adopted, the operator's physical, sensory, and cognitive skills, and the level of effort exerted. Direct feedback and knowledge of results inform operators whether they have selected the correct strategy and are exerting sufficient effort. In addition, such information allows operators to improve their knowledge and skills through practice, thereby creating additional capabilities to apply to the tasks. However, operators may not be consciously aware of every task and incidental variable, the processes underlying decisions and actions, or the effect of different environmental factors. Thus, the level of workload that is experienced by operators is limited by the content of consciousness and may be modified by preconceptions held by the operators about workload.

IMPOSED WORKLOAD

Task analyses are used to define the inputs needed and outputs required in advance of the design or construction of a system. They may specify the environment in which the task is to be performed, the skill and knowledge requirements for operators, likely sources and types of errors, and time requirements and schedules. However, the workload to be imposed on the operator can only be estimated by such analyses because workload is primarily a human-centered rather than a task-centered variable (Ref. 7) and may be influenced by a variety of factors in addition to task specifications. Furthermore, the workload imposed by the total task and experienced by the operator may be considerably different than one would expect from an analysis of those components that are evident.

Task Objectives

In general, human behavior is goal directed; actions are performed and information is processed to accomplish some objective. The goal may be expressed generally, leaving the operator free to select among a variety of strategies, actions, and solutions. Alternatively, the goal may include specific constraints and requirements. The objectives of the task may define an upper or lower limit or provide a range of acceptable performance on relevant variables. Even if the criteria are not explicitly stated, the fact that an experimenter measures one variable rather than another, or that information is given about one parameter rather than another may provide implicit information to an experimental subject about what is expected or considered important. Thus, such factors as the level of precision required of or suggested to the operator for speed, accuracy, efficiency, creativity, or reliability may vary widely from one activity to the next.

Task objectives may or may not be influenced by the level of automation provided to assist the human crew of a complex system. For example, safe flight is always the goal of any trip by air, yet the physical environment in which such a flight is expected to occur and the number of crew members required is often determined by the level of automation provided. The unacceptable consequences of an unaided human error or performance deficit may prompt machine aiding in the hope that the required level of performance can be met. Conversely, the availablity of automated features may lead to additional task requirements, simply because the machines alone or in a supporting capacity make better performance possible. One potentially negative consequence of this latter possiblity is that the human operators of a highly automated system can no longer achieve the required performance criterion should the automated system fail. For example, the pilot of an advanced helicopter flying nap-of-the-earth missions against enemy targets at night under adverse weather conditions, cannot "see" to fly without night-vision aids which also display images and information transmitt by sensors and he cannot simultaneously control the vehicle, navigate, and operate weapons systems without stability and control augmentation systems.

Thus, technology has made it possible for human operators to conduct more sophisticated missions and operate under more difficult conditions than their earlier counterparts (Ref. 1). As a result, the electronic systems designed to aid pilots may actually complicate their job. They may be confronted with too much information to be assimilated and acted upon and be, in the words of one sceptical pilots, "killed with kindness". They may have to operate in a situation where successful performance is impossible without the automated systems. Yet, should any or all of the automated systems fail, a pilot or astronaut may still have to land the vehicle safely or a nuclear power plant operator must resolve an emergency to insure their own survival and the success of the mission.

Task objectives should be a major factor in assigning crew duties or selecting functions to automate. Functions that are required to satisfy system goals should be given primary consideration. Less critical features might be automated if, and only if, their automatic performance unloads human operators to allow them to perform other, more critical, tasks for which they are more essential. Task objectives themselves are rarely determined or modified by a machine in current systems; this function is still reserved for human managers and operators. In the future, however, subsystem, and eventually system, goals may be formulated by robots or expert systems that have been programmed with the decision making processes and value systems of their designers and programmers.

Environmental Variables

The physical environment of a task is created by the location (e.g. on earth, undersea, at very low or very high altitudes, or in space), climate (temperature, humidity, air quality, vibration, etc), workstation layout, noise and lighting levels, and degree of threat from natural or man-made sources. The social environment is created by the interactions among physically present members of a crew or with others via voice, video, or computer link. The environment's impact may be indirect or direct and, in fact, some tasks may be impossible to perform in some environments, no matter how much effort an operator exerts. For example, identical tasks performed in a non-judgemental environment with no ego- or life-threatening consequences of poor performance (or the same task performed in a more threatening environment) may impose different levels of workload because operators may adopt different strategies, change their performance criteria or experience differing stress. Well-learned behaviors performed "automatically" and with minimal workload in a simulator may require considerably more attention and additional effort to perform in space under weightless or reentry conditions or during high-noise, high-virbration nap-of-the-earth helicopter flight. Clothing designed to protect operators from hostile environments, such as radiation or heat protection suits, space suits, or diving gear, although necessary, may further increase the difficulty and discomfort of working in nonoptimal environments.

Tasks performed in environments that require life support systems impose additional requirements including the need to control and maintain the environment itself (Ref. 5). Temperature, air quality, and cabin pressure are but a few of the concerns facing the operators of vehicles operating in such environments. In general, machines have been delegated the primary responsibility for monitoring and maintaining systems necessary to sustain life. These systems require an operator's attention only if they malfunction, much as the human autonomic nervous system maintains homeostasis without the conscious attention or control of the individual. The absolute requirement that such systems function continuously and reliablity, however, make them a continuing concern for the human crew. Periodic monitoring is usually required just as individuals monitor the state of their internal systems with annual physical exams or other self-checks.

Task Structure

Temporal organization. Most activities have an organizational or procedural structure reflected in the duration of the task, the rate and order in which task elements must be performed, and the degree to which task elements can be deferred. For some activities, formal procedures may govern every aspect whereas for others the time taken to perform a task and the sequencing of elements may be left to the the operator's discretion. The workload imposed by a task may be either minimally or substantially affected by the time pressure associated with its performance. It is assumed that there is a minimum time required to accomplish component tasks. The time taken to perform a task, is assumed to equal the time required for each component plus the time taken to switch between task components. Time pressure is defined as the ratio between the time required to perform a task and the time available for its performance (Ref. 8). As this value nears unity, workload is assumed to increase.

Even if the amount of time available to perform a task is sufficient, a stressed or busy operator may overestimate how quickly time seems to be passing, and experience even more time pressure than actually exists. This experience can lead to an operator adopting strategies that are appropriate for a situation that does impose time pressure (e.g. hurrying to finish task elements, experiencing undue feelings of pressure or shedding less important elements) but may not be appropriate for the current situation.

An earlier solution of the problem of time pressure was to add more human operators. Economic factors and the availablility of cheap, light-weight microprocessors have suggested a new solution; automating one or more subtasks. Many forms of automation have been incorporated into modern systems such as aircraft, with the result that crew members are increasingly responsible for more tasks than can be performed in the time available. Performance of transport aircraft in the increasingly complex air traffic control system is made possible only by the addition of stability and control augmentations, navigation command systems, informational displays, alerting and warning systems, and automatic air-ground communications (Ref. 9). The pilot's role in the system has been adjusted accordingly. His role as a system manager reflects the degree to which routine flight functions have been automated so that the majority of his duties have become supervisory. A potential problem with this solution is that tasks necessary for safe operations must still be performed even if the automated systems should fail, placing pilots under even greater time pressure than with the original manual systems, usually under conditions of high stress and uncertainty

System Resources. The resources available to the operator of a modern system include information, equipment (including computers), software, and other crew or support personnel. To some extent, operator workload and system performance may rely on the human operator's ability to manage and use effectively the resources available. Some task elements may require simultaneously the same information, or equipment, or mental or physical resources of an operator and therefore may be difficult to perform concurrently. Other task elements require different resources, or limited amounts of the same resources, and may be performed concurrently with ease.

If an automated system displays summary information about entire mission segments or even integrated relationships among relevant system elements, the operator need perform only a single task at any time -- initiating the automated sequence of events or recognizing the completion of such a sequence. This, obviously, has the potential for reducing the pilot's workload. Integration means much more than the physical connection or networking of devices. It should imply coordination and synthesis in transmitting appropriate and sufficient information in a convenient location or allow complex control actions to be initiated by a simple selection. The format of a display is extremely important -- complex, crowded, unstructured "dumps" of obliquely coded digital data makes the task of extracting information very difficult. For example, replacing multiple dials, in which the same indicator position represented a nominal state by a digital readout requires the operator to read each digital value individually instead of quickly scanning across a set of dials to make certain that all indicators are oriented properly. Alternatives such as graphics, symbology, and shape, color, or position coding as well as an organized sequence of presentation can make information that is known to the system more readily available to the human operator. In addition, computer-generated displays make possible the presentation of many forms of related information in a common format.

If the performance characteristics of the controls and displays through which an operator and an automated system interact fit the operator's mental model of the system, then the resources made available by automation will have greater utility. If they do not match his mental representation, then he must perform additional mental operations to translate back and forth between displays of actions and his internal representations of them (Ref. 1), thereby increasing mental workload and decreasing system efficiency. For example, because automobile cruise control does not have preview of road conditions, it lags in decelerating down hills and accelerating up hills thereby failing to match the driver's learned anticipation of when to initiate a change in acceleration to achieve constant velocity; the operation of the automatic system does not match the operator's mental model of the way the task should be performed.

Operator qualifications

Few tasks are designed without some assumptions about the background and skills of potential operators. The criteria may be related to formal education, physical capabilities, past experience, sex, age, or personality traits , to name a few. Systems are designed to accomodate most potential operators, and, when procedures and training programs are established, it is with the capabilities and previous experience of the potential operators in mind. In research settings, the subject population may be constrained to potential users of the system under investigation or include a random sample of the population in general.

As modern systems are altered by different levels of automation, the training required, assumed knowledge base, and selection criteria for operators may change. For example, a computer programmer might manage a highly automated system more effectively than a pilot who knows a lot about aviation but little about computers. During the transition from predominantly manual systems to predominantly automatic, the role of operators will shift from direct control to management. The qualities associated with success in one, may not be appropriate for the other, and additional training may not provide an adequate solution. If sufficiently well-trained or capable individuals cannot be found to operate advanced systems, then the level of information given to the operators, and thus their understanding of the system, must be simplified so as to allow them to use the system at all. Thus, operators may not have to know very much to operate the system, but they may never understand what they are doing or why.

Incidental Variables

The task variables described above are intended or potential and may not completely describe the workload imposed during actual task performance. If a situation is carefully controlled, the experienced level of workload should be similar to the intended level. However, the level that was intended in advance may be modified by incidental variables specific to the environment, the operator, or the system. For example, environmental conditions different from those that were expected or unanticipated physical and emotional states of an operator may modify the task itself or the operator's perception of it. Errors made by the operator or someone else or a hardware malfunction may have a momentary effect on workload or influence the remainder of the task by altering its structure or organization (Ref. 10). Recognizing and diagnosing unexpected situations may increase workload even if no corrective action is taken. Considerable additional effort may be required to provide a remedy. If an error disrupts the completion of practiced sequences of behaviors, the additional load might be much greater than it would appear. Even if no additional tasks are performed, completing the remaining task elements out of sequence or with conscious attention to details that are normally accomplished automatically may substantially increase workload.

Incidental variables may modify the workload so that what is imposed on an individual during a specific performance of a task may be substantially different from one time to the next or they may simply contribute "noise" to the results of laboratory or simulation research.

Since incidental variables may occur during the most carefully planned task, their potential contribution to workload must be considered. The change in workload associated with their appearance may be calculated and included in a revised post hoc assessment of workload and may be anticipated in determining the envelope within which the task could be performed.

OPERATOR VARIABLES

Perception of Task Demands

Because the operator's understanding of what he is expected to do forms the basis for his actions and experiences, there may be a major discrepancy between the workload of a task as conceptualized by its designer and the workload experienced by a specific operator. With training and appropriate feedback, an operator's perception of what he is expected to do, and how, will more closely match the intended objectives and structure.

Whether an operator views the task as a collection of unrelated and separate actions or as an integrated whole may affect how the task is perceived, whether automatic behaviors are invoked, how strategies are selected, and how resources are used. Experts tend to think in terms of larger scale units than novices (Ref. 1) They consider a group of related tasks as functional units to avoid being buried in the minutiae of recognizing and performing each sub-element. They perform component elements without conscious attention, recognize complete patterns of information and initiate automated sequences of related actions with a single decision, thereby reducing workload. Furthermore, they can relate the workload of the current situation to many previous, similar occurrences of the task, and perceive the current experience relative to past ones, having to pay special attention only to the things that are different. Components of such tasks are performed relatively automatically and there is little about any single occurrence of the task to be remembered specifically.

The accuracy of operators' perceptions of the task structure and requirements and their understanding about what resources are available to them may suffer with the addition of automation. If operators perceive their new role to be essentially passive or superfluous, then the likelihood that they will interact with or monitor the performance of automated systems may decline until the operators are no longer performing even a managerial or supervisory role. This may occur as a result of complacency, alienation, or lack of interest.

Operator Strategies

The goals and structure of some tasks require adherence to particular strategies if good performance is to be achieved with acceptable workload. For example, some tasks (Ref. 12) must be done immediately because they are so important or because they will become more difficult or impossible to do if there is any delay. Other tasks can be deferred for several minutes with no loss of performance or change in task difficulty, but they must be done within some time window. The remaining tasks, such as planning and preparing for future events, are still required for safe operations but are not time-critical. These activities can be deferred usually should more time-critical tasks intervene but the operator must keep ahead on planning tasks and not be caught short as deadlines approach.

The role of strategies is particularly important because it is this factor that determines which of the available resources are used, the level and type of effort exerted, and the interim system performance goals and informational feedback considered relevant. An operator may allocate different amounts of his resources to a task, or some aspects of it, and may adopt a variety of strategies to accomplish his perception of what is required. The strategies selected may depend on the operator's experience and level of understanding of the task or the desire to select an easier approach or one that would take advantage of his skills and strengths. Whether or not an operator uses optional automated features in developing and executing his strategies depends on his understanding of the automatic systems, his opinion of their utility and reliability, and the importance placed on their use.

Operator Capacity

Whenever a task is performed, particular capabilities and resources are required from the operator. Such resources may include physical, sensory, and cognitive processing skills, and a general knowledge base. Workload may be influenced by the degree to which an operator has the expected skills and background. An experienced operator will adopt efficient strategies, use established patterns of motor response, and exert appropriate effort in a timely way, thereby minimizing workload. In addition, skilled operators are more likely to have an accurate perception of task goals and performance criteria, thereby increasing the probability that their behavior will be efficient and effective.

Unexpected events or failures may affect skilled operators differently than unskilled. Equipment failures, environmental changes, or errors may disrupt automatic sequences of behavior for the trained operator (thereby increasing his workload). Worse, however, these abnormalities may go unnoticed by the confused novice. Skilled operators may recover from their own errors or equipment failures with little increase in workload, whereas novices may not notice a problem until it has become critical or they may fail to compensate for it effectively. An operator experienced in the control of a basic mechanical system might not understand the additional functions and structure of an automated system. By contrast, an operator that was trained as a high level user of a fully automated system might understand the computer-based management system, but have little knowledge of the underlying mechanical functions. Thus, the types of failures that could be recognized or resolved effectively, and the associated level of workload, are influenced by the level of operator training and skill.

The concepts of capacity and resource allocation have intuitive appeal in the analysis of workload. However, they are difficult concepts to deal with operationally (Ref. 7) and do not provide sufficiently well-defined structures to predict or measure workload. The apparent "capacity" of an individual to perform work is a very complex function of the structure of the task itself, and the operator's training, strategies, motivation, and ability to download simple functions and groups of related tasks to lower levels of activity. Thus, there is no apparent value in invoking the concept of exceeded capacity. Given experience, appropriate task structuring, and performance feedback, exceptionally complex and objectively loading tasks can be performed successfully with apparently comparable levels of workload. Furthermore, by identifying task parameters and structures that demand the same processing resources or response mechanisms concurrently, automation of one or more functions could alleviate predicted or existing problems.

Operator Behavior

Not only does an operator direct his "resources" toward a task, but he exerts effort in a variety of ways. Physical effort is the easiest to conceptualize, observe, and measure, yet its contribution to the workload in modern systems is diminishing. Mental effort, although not directly observable, may be inferred from task performance, physiological recordings, and subjective reports but it is difficult to quantify directly. It serves as a potent intervening variable between measurable stimuli and measurable responses.

The human mind is never still, never unused. The thoughts of an operator occupied by the most tedious and boring jobs may be filled with complex and detailed daydreams, intricate plans, or philosophical musings. The task itself may <u>require</u> no mental work, but the individual may engage in elaborate mental activities nonetheless. Such mental activities are not required by the job; they still occupy the operators mind - - a spontaneous (and relatively invisible) secondary task. Certain mental processes may be thought of as more difficult, more loading, or more capacity-consuming than others, yet there is no objective mechanism with which this can be measured. It might be more parsimonious to characterize the mental effort devoted to a task by the degree to which the operator's mental facilities are "captured" by and devoted to achieving the goals of the task. The problem remains, then, one of measuring the degree to which a task captures or consumes the thoughts of an operator.

An operators' contribution to a man-machine system can be characterized by the degree to which different types of behaviors (e.g. monitoring, sensing, information processing, interpreting, decision making, information storage, and control) are required. Each behavior requires different resources and some may be performed more effectively by a human operator, some by a machine. Different types of behavior may correspond to different levels of mental or physical effort (Ref. 9, 11). Skill-based behaviors (corresponding to conventional manual-control activities in which the operator receives immediate feedback about his actions) may be performed automatically with little conscious thought and are likely to contribute little to experienced workload. Rule-based behaviors (including procedural activities performed according to established sequences of familiar actions, learned algorithms, habitual patterns, information processing, and short-term planning) involve a higher level of processing and are thus associated with greater mental workload. Knowledge-based behaviors (requiring operators to perform complex interpretation and decision making, and derive novel solutions with limited or delayed feedback) require the highest level of processing and thus the greatest mental workload.

Many lower level, less mentally taxing tasks are prime candidates for automation. If rules exist for the performance of a task, or if well-defined, closed-loop control is required, then it is likely that the function could be performed by a machine. This leaves the more demanding tasks for the human operator. While it is in this domain that humans continue to out-perform machines, these behaviors impose the maximum levels of workload and the locus of the load is within the operator where it is difficult to observe or assess. In addition, these types of behavior are the most difficult to learn and the easiest to forget because they are the most abstract. Thus, assigning skill-based and rule-based behaviors to machines may only shift the source of load within the operator from direct sensation or physical control to interpreting, problem-solving, deciding, and predicting; high workload tasks.

PERFORMANCE

Operator performance is a critical element in translating imposed workload into experienced workload. Performance not only provides a kind of input to the system (operator's experience their own performance), but it also provides observable outcomes that can be monitored and measured. It is assumed that operators generally do their best to achieve their perception of the task requirements. In addition, they may compare how well they are doing to a previously established standard, and, if there is something to be learned, they may adopt more efficient strategies, download functions to lower levels of activity, or modify their behavior to improve performance. Thus, with human operators, the output is always fed back to become an input even when no feedback mechanisms are explicitly added by the designer and the existence of the feedback is not observable from the outside of the operator's body.

For tasks that include many levels of automation, evaluating the performance of human operators from the outside may be difficult, as the majority of their behaviors may be monitoring, sensing, processing, interpreting, decision making, and storing information - - all cognitive processes that are invisible to an outside observer until an overt response in made. Since many stabilization and "tight loop" control activities are now performed by machines, the results of the operator's efforts in automated systems may be witnessed only indirectly and infrequently by an outside observer or by the operator himself.

There is no simple relationship between workload and performance (Ref. 8), even though the primary reason given for measuring workload is to predict performance (Ref. 12) Then, why not measure performance directly, especially since performance can be measured relatively more easily than workload? The answer is that a high level of performance can be maintained as task demands and mental workload gradually increase - - right up to the point where the operator's abilities are exceeded (or he lowers his performance standard) and performance deteriorates abruptly. It has been assumed that, if suitable measures of mental workload can be found, they would be better predictors of future performance than measures of current performance. In other words, mental workload may be the best prediction of what might happen to the system if task demands were increased still further.

Excellent performance may be found with easy tasks that impose low workload or with difficult tasks that challenge an operator to mobilize more resources. On the other hand, poor performance may reflect extreme effort in response to an impossible task or inadequate effort in response to an easy task. In addition, performance may be necessarily evaluated relative to an external standard that is not appropriate or reasonable for the current situation. Nevertheless, the relationship between workload and performance is important for practical reasons because one may be sacrificed for the other; operators may shed tasks to maintain acceptable workload or increase effort to achieve consistent performance. Achieving acceptable performance for the required length of time with an acceptable level of operator workload is a typical design goal. Therefore, a key issue is whether or not the operator can do what is required for as long as is necessary with some margin of safety. The potential for trading off performance to reduce workload, or increasing effort to protect performance, can be left either to the discretion of the operator (within limits), or modified by additional training, different procedures or task requirements or the provision of automated functions. Although failure to perform a task adequately may well suggest a workload-related problem, analysis of the entire situation is required to determine whether variation in one (e.g. changes in performance) reflects a concomitant change in the other.

It may be useful to discriminate tasks that cannot be performed because of obviously inadequate information, inaccessiblity of controls, or hostile environment, from those that can be performed, but at the necessary cost of high workload. In other words, one should not substitute the term "workload" for performance decrements related simply to design deficiencies. Furthermore, human operators have physiological and psychological needs that, if not met, may negatively impact their ability to perform a task. (Ref. 4) Human performance deteriorates rapidly when physiological needs for nourishment, sleep, comfort, and health are not met. In addition, performance may be degraded by psychological factors, such as prolonged periods of high stress, fear, conflict, or inactivity. Blaming "workload" for the consequent deterioration in performance is neither correct nor useful.

PERFORMANCE FEEDBACK

The operator's perception of how well he is performing a task on a moment-to-moment basis (as in a closed-loop control situation) or in a more general sense (as in a management or supervisory control task) may influence his perception of the task, the strategies he selects, the effort he exerts, and his subjective evaluation of the experience. Some forms of feedback provide operators with limited information about the general state of the system whereas others provide information about the effects of the operator's own actions. Operators may choose to change their strategies, exert additional effort, or commit different resources on a task as a consequence of knowledge of results. With either direct feedback (such as proprioceptive feedback of control movements) or knowledge of results (such as a display of vehicle deviation from the desired course), operators' general knowledge and specific skills may be improved through practice, thereby creating additional capacities to apply to subsequent tasks.

An operator's ability to assess the immediate situation is clearly dependent on the currency of the informational feedback. Control decisions based on the operator's knowledge of the system's state are transformed into mechanical action by exercising well-learned patterns of response or mechanized subsystems. Thus, the accuracy of the operator's assessment is a critical element in determining subsequent behavior, whereas the actual control input or command reflects a relatively trivial execution of a potentially complex mental process. Automation can reduce an operator's workload if it provides displays and controls that match his mental representation of the tasks and if the information is converted to a common medium and presented in an integrated form. Direct proprioceptive feedback may also provide necessary information to the operator about the quality of his control input, particularly if the response of the system is delayed. For example, in the F-18 aircraft, electrical signals from an isometric controller replaced the combination of control by human and mechanical linkages. Compliance in the control stick was provided to replace the lost proprioceptive feedback, when pilots had difficulty in flying without any "feel" to the control stick (Ref. 1).

Automation can mask the relationship between cause (operator action) and effect (change in the state of the system) by delaying in time or distorting in character the isomorphism between operator actions, system state, and knowledge of results with different feedback signals from different subsystems occurring at different times as a result of a single action. Furthermore, the form of knowledge of results that is provided is generally negative in nature; that is, the status of automated systems may not be presented unless there is something wrong. Another problem in systems with multiple automated sensors is that information from various sources may not be presented in a usefully integrated form, or information from one source might not agree with that from another. The format and content of the display might not relate to the operator's conception of the task and the cognitive skills and language required for interaction are different if control is effected directly than if it is effected indirectly via computer interface.

The presence of multiple, delayed and distorted feedback loops make it difficult for operators to estimate the instantaneous state of a system or develop functional mental models of it. This may lead to situations in which errors are likely. People tend to make small slips, deviations, or errors continuously in the same way that any active closed-loop mechanism makes errors; when there is adequate feedback, they immediately tend to correct these errors. Thus, human reliablity may be a matter of providing timely and meaningful feedback. However, undetected and uncorrected errors are likely when such feedback is delayed, ambiguous in associating operator actions with system states, or lacking altogether. The occurrence of human errors, particularly errors that have substantial impact on the system, surely increases the workload subsequently imposed on an operator. Additional errors associated with inadequate feedback aggravate the situation. This may continue to be a serious problem as automation is increased.

Thus, the workload that is actually imposed on a specific operator during a given performance of a task is the sum (or the remainder) of the intended task demands, modified by the environment in which the task is performed, filtered by the perceptions of the operator, his capacities, strategies, and behaviors, and the resulting performance. Under controlled conditions, with practiced operators, these potential sources of variability may have little impact. However, in a realistically complex setting, many or all of these additional factors may determine the level of workload actually imposed by the task. It is this phenomenon, then, that is reflected in the experience of the operator.

[illegible]

Each individual may experience the workload imposed by a task differently as a consequence of previous experiences, biases, and different perceptions of the nature and purpose of a task (Ref. 8, 13). To some, the workload imposed by a task may be completely defined by its structure, temporal organization, and goals, (regardless of whether the performance criteria are met). To others, the effort exerted, or the degree to which the task captures their attention, determines the workload experienced. To yet others, success or failure in meeting the demands of the task are a key element in their experience of workload. Other factors such as stress and fatigue are responsible for the level of workload experienced by some, while frustration or time pressure may create different levels experienced by others.

Not only is there considerable variability in the dimensions that different individuals might include in a definition of workload (perhaps no more than a semantic issue), but it has been found in laboratory and simulation research that subjective evaluations of experienced workload by different people covary with different task variables (Ref. 14). It is possible that the subjective experience of workload is a weighted average of the "amounts" of the different factors that are present in a situation (e.g. task difficulty, uncertainty, time pressure, stress, and success or failure). The "weights" applied by different people to various elements of objective and experienced workload may vary from one person to the next, however, although some factors have been found to be more common (e.g. task demands, stress) than others (e.g. fatigue, time pressure). Even though some variation in such biases or individual definitions of what affects each person's experience workload has been found within individuals across time, the differences were not great (Ref. 16).

One benefit of differentiating the subjective experience from the demands that are imposed on an individual is methodological; it suggests a potential source of the variability that is observed in ratings obtained from different individuals who experienced apparently identical situations. Furthermore, if individuals feel loaded, then it is likely that they will behave as though they are loaded. That is, they may adopt strategies appropriate for high workload conditions (which may or may not be appropriate for the current situation) and experience physiological changes associated with high workload. Thus, the importance of the subjective experience of workload may extend beyond its influence on subjective ratings, as it may affect behavior (and thus, performance) as well as physiological functions that reflect emotional stress or workload.

An important point to remember, however, is that the subjective experience of workload is not necessarily the same as a subjective rating of workload. In order to provide an estimate or evaluation of the workload experienced, an individual can only refer to his conscious experience, or his memory of an experience. By contrast, a rating of workload may reflect the operator's conscious perception of the task demands and his own overt responses to them. The result is that a rating may or may not accurately reflect one's internal or mental behaviors and processes (Ref. 15), depending on the individual's skill in introspection and the degree to which the relevant factors are available for conscious inspection.

The relationship between experienced workload and different levels of automation is not clear. The intention of automation is that is reduces the number of tasks to be performed which should diminish the workload experienced. However, as manual control tasks, for which assessments might be made with relative ease, are replaced by supervisory and management tasks that involve primarily mental behaviors (that are less accessible to conscious inspection) and as less information is available about success or failure, the factors responsible for different experiences of workload are less obvious. In addition, even though control may be assumed by a machine, the operator is still ultimately responsible for the success of a mission. This, coupled with the fact that automation is often accompanied by additional responsibilities and requirements, may result in an increase in experienced load. Other factors, less directly tied to the task, may influence experienced workload as well. The operator's satisfaction with his new "automated" job, his understanding, trust, and acceptance of the system, his ability to interact with the system and recover from errors may have considerable impact on his perception and experience under different levels of automation (Ref. 5)

DEFINITION OF WORKLOAD-RELATED QUESTIONS

It is essential to have a precise formulation of the question to be answered by a workload analysis. For example, the question, "Can the operator do more?" might be addressed by a different analytic approach than the question "Can this task be performed under weightless conditions with the same workload?" Other questions, still within the legitimate domain of workload analysis might include "How many crew members or how much automation is required?" or "Is this display format preferable to that one?" Some workload questions may relate primarily to the structure and organization of the task itself, some to the range of environments in which the task may be performed, and yet others to the effort or emotional cost to the operator to perform the task. Some questions may not relate to workload at all. Instead, they should be considered as equipment design problems, matters related to excessive stress or fatigue, or labor/management issues, without even invoking the issue of workload.

The problem of measuring workload under different levels of automation is great, because the nature of the workload and the operator's perception of the task is likely to differ. An observer is faced with the task of calculating the amount of physical or mental workload that was reduced by the addition of automation and also the subsequent change in mental workload imposed by the requirement to monitor and understand the complex, computerized system providing the automation. In addition, it may seem desirable to compare measures of "system workload" to measures of operator workload to assist in the decision of which tasks should be automated and which assigned to human operators. This task may be difficult or impossible as it is even less clear how measures of machine load might be equated with measures of human load.

ALLOCATION OF FUNCTION

Human operators, machines, and computers involved in the control of modern systems are elements of an intelligent organism (Ref. 5) having sensors, effectors, homeostatic control mechanisms, and intelligence. In a well-designed system, they should cooperate in a symbiotic fashion so that each performs the activities for which it is best suited. The decision of whether man or computer or a machine should perform any function and the degree of independence one system component has from any other should be determined by an assessment of the relative capabilities of each. There are many tasks that can be performed interchangeably by men or machines, and an equal number that should be performed by one instead of the other. There are instances where a machine might be more capable of guiding and monitoring the human operator, and those when the operator should retain supervisory control. However, there is no standardized or accepted theory-based methodology available to systematically allocate functions between automated systems and human operators. Similarly, there is no common basis for weighing the relative costs of automating a function against the potential improvement in the state of the operators or the performance of the system. Other concerns may be considered as well. In selecting the components of a complex system it is usually not so much which will so a better job, as which will do an adequate job for less money, less weight, less power, or with a smaller probability of failure and less need for maintenance (Ref. 1).

Modern microprocessor technology and display systems make it possible for computers and machines to perform some of the functions traditionally assigned to human operators (e.g. monitoring, computing, warning, and control). Routine, small-scale, well-defined tasks automatically controlled with little need for human intervention are likely to reside in all levels of modern systems. Tasks that require perceptual or physical abilities outside the range of human capabilities or risks for humans should be performed by machines. In addition, computation, storing and recalling large amounts of data, precise, continuous and repetitive tasks, and detecting infrequent signals are likely candidates for automation. Finally, it might be wise to automate tasks that require long attention spans or those that humans do not like to do (Refs. 4, 5). Even if the tasks that are automated are not themselves critical, such automation may relieve operators to attend to more important activities. Humans are serial processors, and there is cost in time and additional workload for them to switch among activities and keep track of multiple concurrent responsibilities. Thus, automation might be considered to alleviate situations in which multiple tasks have to be performed concurrently or where a number of critical events occur at the same time.

Tasks that require the most complex levels of decision-making cannot yet be automated, nor can functions that require value judgements. Critical, large-scale, or less predictable activities may require greater human assistance, and only humans can serve as innovators with current technology. Humans should be assigned tasks that require inductive reasoning, solving unique or novel problems, or learning from experience. If a task entails interpreting or processing unexpected or unpredictable events, or the detection of subtle patterns in very noisy environments, then a human might be better able to perform it than a machine. In addition, humans must perform tasks for which rules and procedures cannot be established and should be allowed to perform those tasks which they enjoy (Refs 4, 5). Operators want to retain the ability to select among automated features and to intervene in their operation. They are more likely to accept automation of activities that they cannot perform adequately or of tasks that can be performed more reliablity through automation that also distract them from performing other, more critical, tasks (Ref. 1).

To a human operators, performing any task has an associated cost. This "cost" may be measured in terms of operator workload, loss of motivation, fatigue, additional requirements for training and proficiency maintenance, or performance degradation. There is only so much that an operator can do within the time constraints of a mission; thus intelligent tradeoffs must be made so that only those tasks for which humans are particularly suited are assigned to them and other tasks are off-loaded by automation. Humans are readily bored by routine, repetitive tasks and become inattentive and make mistakes following extended periods of such tasks. They are limited in strength, endurance, sensitivity to some things, response speed, precision, ability to store and recall large amounts of information precisely, and the environments in which they can operate safely and comfortably. Thus, tasks that require repetitive and precise monitoring or control inputs might be better performed by a machine, leaving the human operator to the supervisory and decision making role for which he may be better suited. By selectively providing different levels of automation, innate capabilities of humans can be capitalized upon and limitations avoided to come closer to an optimal level of system performance and workload of man and machine.

HOW TO AUTOMATE

Computer technology makes it possible to develop dynamic, integrated, and comprehensive automated designs for future systems. A committee convened by the National Research Council for the purpose of studying automation in combat aircraft (Ref. 1) and a workshop on automation and space (Ref. 5) made a series of recommendations about the design of advanced, highly automated systems. Adopting a systematic approach is critical so that core functions are automated first and subsequent levels of automation are added in an organized way. Piecemeal automation is costly, confusing to operators, and results in partial solutions that are not adaptable to future missions. Computers have made it possible to display an amazing overload of information. The next challenge will be to display just what is needed, when it is needed, in an integrated and user-friendly format.

If system enhancements are not reliable and readily available to the crews, they will be circumvented and ignored. Extremely poor system performance will be obtained if systems designed for automatic control are controlled manually because of design deficiencies or warning systems are dissabled because of unacceptably high false alarm rates. Redundancy is important as well to allow operators to rely on the advanced systems with confidence, although operators must be sufficiently trained on failure modes, particularly multiple failures, that mission safety can be maintained in the event that the automated systems are degraded or fail. Acceptance by the operators is critical, as they will not use what they do not accept. Thus, systems should be designed to allow operators flexiblity in operating the equipment according to their preferences and to maintain proficiency with multiple system configurations as long as system performance and safety are maintained. Information to facilitate operator decisions should be provided and if the decision-making process itself is to be automated, the procedures should be related to the decision rules actually used by human operators.

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Automation is only one of many ways to achieve acceptable levels of workload, reduce errors, and improve (or enhance) performance. Other alternatives such as revised procedures, training and improved system design might be alternatives to additional automation. The technical feasibility of automating a function should not provide the only justification for doing so. The use of automatic, intelligent machines will not necessarily reduce the amount of work that humans do, but may permit the enhanced performance of more and more complex tasks. The explosion of automation will continue, but its pace and design should be tempered by understanding of and concern for human operator workload.

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