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A Human Factors Comparison of Airborne Mine Countermeasures Controls and Displays as Installed on the CNS/ATM MH-53E Helicopter and the Legacy MH-53E Helicopter

Jeffrey S. Farlin
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Jeffrey S. Farlin entitled "A Human Factors Comparison of Airborne Mine Countermeasures Controls and Displays as Installed on the CNS/ATM MH-53E Helicopter and the Legacy MH-53E Helicopter." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Richard Ranaudo, Major Professor

We have read this thesis and recommend its acceptance:

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Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jeffrey S. Farlin
May 2008

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ABSTRACT

The United States Navy has begun an initiative to upgrade the existing MH-53E aircraft from an analogue gauge cockpit to a digital glass cockpit. In order to assess the capability of the digital cockpit to perform the Airborne Mine Countermeasures (AMCM) mission as effectively as the analogue cockpit a human factors engineering analysis was conducted comparing the pros and cons for each cockpit. The primary focus of the paper was on the physical ergonomic characteristics of the AMCM cockpit. A limited analysis was also conducted evaluating some of the physical and mental workloads required for executing an AMCM mission. To determine which cockpit could best support the AMCM mission, distances from the pilot to AMCM controls and displays and distances between AMCM displays were measured. The number of key strokes and the mental calculations required to complete certain tasks were also measured. It was found that the AMCM controls and displays in the MH-53E digital cockpit were better grouped, more salient, and better labeled than the analogue cockpit. It was also found that the physical and mental workloads in the digital cockpit were less when performing certain AMCM related tasks. Overall, from a human factors perspective, the digital cockpit was determined to be better suited in carrying out the AMCM mission.

PREFACE

The results contained within this thesis were obtained during United States Department of Defense sponsored Naval Air Systems Command projects conducted by the Naval Air Warfare Center, Patuxent River, Maryland. The discussion of the data, conclusions, and recommendations presented are the opinions of the author and should not be construed as an official position of the United States Government, United States Department of Defense, the Naval Air Systems Command, or the Naval Air Warfare Center Aircraft Division, Patuxent River, MD.

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LIST OF ABBREVIATIONS

#	Number
AC	Aircraft
ADI	Attitude Direction Indicator
AFCS	Automatic Flight Control System
AGL	Above Ground Level
AHRS	Attitude and Heading Reference System
AMCM	Airborne Mine Countermeasures
AWSTS	Airborne Mine Countermeasures Weapon Systems Training School
CNS/ATM	Communications, Navigation, Surveillance/Air Traffic Management
DOD	Department of Defense
DTG	Distance-To-Go
DTK	Desired Track
EGI	Embedded Global Positioning System/Inertial Navigation Unit
ENT	Enter
FIG	Figure
FOM	Figure of Merit
FOV	Field of View
FT	Feet
GEOSIT	Geographical Situation
GPS	Global Positioning System
GSDA	Ground Speed and Drift Angle Indicator
HM	Helicopter Mine Countermeasures
HMIDD	Human Machine Interface Design Document
HSI	Horizontal Situation Indicator
IFF	Identification Friend or Foe
INU	Inertial Navigation Unit
KTS	Knots
KGS	Knots Ground Speed
KIAS	Knots Indicated Ground Speed
LBS	Pounds

LCD	Liquid Crystal Display
LSK	Line Select Key
MFD	Multi-Function Display
MOP	Magnetic Orange Pipe
MSN	Mission
NATIP	Naval Aviation Technical Information Product
NAVAID	Navigation Aid
NM	Nautical Miles
PG	Page
PGD	Page Down
PGU	Page Up
RADALT	Radar Altimeter
RNAV	Area Navigation
RNP	Required Navigation Performance
SHP	Shaft Horse Power
SRC	Stimulus-Response Compatibility
TRK	Track
TSI	Tension and Skew Indicator
TTG	Time-To-Go
YDS	Yards

DEFINITION OF TERMS

Anthropology: the scientific measurement and collection of data about human physical characteristics and the application (engineering anthropometry) of these data to the design and evaluation of systems, equipment, and facilities.[1]

Anthropometric dimensions: measured dimensions that describe the size and shape of the human body. These dimensions are often presented in the form of summary statistics that describe the range of body dimensions that are observed in a population.[1]

Design Eye Point: the point in space located at the sitting eye height dimension of the 50th percentile average aviator measured vertically above the neutral seat reference point.[2]

Device: generic term often used within the AMCM community to refer to a particular AMCM weapon system.

Ergonomics: an interdisciplinary field of study that seeks to design tools, equipment, and tasks to optimize human capabilities.[3]

Neutral Seat Reference Point: the location of the seat reference point when the seat is adjusted to the midpoint of vertical adjustment.[2]

Reach Zone 1: Restraint Harness Locked - Functional Reach. This zone includes the area that can be functionally reached and actuated by any crewmember of the population defined by the acquiring activity when located at the appropriate design eye position fully restrained and equipped without stretch of arm or shoulder muscles.[4]

Reach Zone 2: Restraint Harness Locked - Maximum Functional Reach. This zone includes the area that can be functionally reached and actuated by any crewmember of the population defined by the acquiring activity when located at the appropriate design eye position fully restrained and equipped with maximum stretch of shoulder and arm muscles.[4]

Reach Zone 3: Restraint Harness Unlocked - Maximum Functional Reach. This zone includes the area that can be functionally reached and actuated by any crewmember of the population defined by the acquiring activity when located at the appropriate design eye position with the shoulder restraint fully extended and the arms stretched full length.[4]

Salience: A pronounced feature or part; a highlight.[5]

Seat Reference Point: The point at which the center line of the seat back surface

(depressed) and seat bottom surface (depressed) intersect. When the seat is positioned at the midpoint of the adjustment range(s), this intersection point is called the neutral seat reference point (NSRP).[1]

SECTION I: INTRODUCTION

1.1 Background

In response to recently imposed functional requirements the United States Navy and United States Marine Corp has initiated an effort to upgrade the CH-53E (Marine Corp version, Figure 1) and MH-53E (Navy version, Figure 2) helicopters from an analogue cockpit to a digital cockpit. This upgrade is referred to as the Communications, Navigation, Surveillance/Air Traffic Management (CNS/ATM) upgrade as it improves on the current communications, navigation and surveillance suite which allows for increased operability in the airspace network, particularly when operating in foreign countries. The necessity to transition to the CNS/ATM cockpit, herein referred to as “glass cockpit”, was driven by the functional requirement for all MH/CH-53E helicopters to have the capability to meet Required Navigation Performance (RNP) Area Navigation (RNAV) requirements. One of these items is a digital display showing aircraft position, NAVAIDS, waypoints, etc. Current, or “legacy”, CH/MH-53’s do not have this capability. As such, major changes were required, and the most significant were those involving cockpit displays and layout. The purpose of this analysis was to focus on those changes specific to Airborne Mine Countermeasures (AMCM) controls and displays and to ultimately determine, from a human factors perspective, if the CNS/ATM MH-53E is an improvement over the legacy MH-53E in carrying out the AMCM mission.

Figure 1. CH-53E Super Stallion.

Source: Twomey, P. J., “H-53E Super Stallion/Sea Dragon Auxiliary Power Plant Power Survey,” Masters Thesis, Aviation Systems Dept., University of Tennessee, Knoxville, TN, 2004.

Figure 2. MH-53E Sea Dragon.

Source: Twomey, P. J., “H-53E Super Stallion/Sea Dragon Auxiliary Power Plant Power Survey,” Masters Thesis, Aviation Systems Dept., University of Tennessee, Knoxville, TN, 2004.

1.2 Aircraft Description

1.2.1 General

Both the CH-53E (Marine Corp) and MH-53E (Navy) helicopters are in the process of receiving the glass cockpit upgrade. The focus of this paper is on the MH-53E since AMCM controls and displays only apply to that airframe (the CH-53E does not conduct the AMCM mission). Deliveries of the MH-53E, manufactured by Sikorsky Aircraft Corporation, first began June 26, 1986. The MH-53E utilizes a fully articulated, seven-bladed main-rotor for its primary thrust and a four-bladed tail rotor for anti-torque control. It is the most powerful helicopter employed by US forces.[6] This power comes from three General Electric turbine engines (the T64-GE-419) capable of producing 4750 shaft horse power (shp), each with a contingency power setting that produces up to 5000 shp.[7] The empty weight of the aircraft is 36,745 lbs with a maximum gross weight of 69,750 lbs.[6] The MH-53E has an internal fuel capacity of 21,844 lbs of fuel which, at sea level on a standard day, allows for a maximum range of 700 nautical miles (nm) and a maximum endurance of 6.6 hours.[6] Flight path control of the MH-53E is effected through three primary controls—the cyclic, collective and anti-torque pedals. Cyclic inputs may be made longitudinally (fore and aft) and laterally (left and right). Movement of the cyclic tilts the tip path plane of the rotor head to the desired direction thereby moving the helicopter towards that direction. Collective inputs are made vertically (up and down) and control the amount of thrust that the main rotor head generates by collectively changing the pitch of all main rotor blades at the same time. Collective movement controls the

vertical climb and descent rates of the aircraft. Pedal inputs control the amount of thrust generated by the tail rotor. This counters the torque effect of the counter-clockwise turning main rotor and provides direction control of the aircraft.

1.2.2 Legacy Cockpit

The current configuration of the MH-53E legacy cockpit is presented in Figure 3. In executing the AMCM mission certain flight and navigation instruments are utilized more than others. They are the Attitude Direction Indicator (ADI), Horizontal Situation Indicator (HSI), Tension and Skew Indicator (TSI), Radar Altimeter (RADALT), Groundspeed and Drift Angle Indicator (GSDA), and the MK-108 Mod 0 Display Unit. Flight displays are provided for both the pilot and copilot. All instruments are located on the instrument panel

Figure 3. MH-53E Legacy Cockpit.

Source: LCDR Jeff Farlin, Airborne Mine Counter Measures Weapon Systems Training School (AWSTS), Norfolk, VA, 2007.

with the exception of the single MK-108 which is located on the lower console between the pilot and copilot seats.

The ADI, shown in Figure 4, provides aircraft pitch and roll attitudes to the pilot and copilot. Additionally, turn rate information as well as slip and skid (or lateral acceleration) and some navigation information is also provided. Warning flags alert the crew of instrument failure and erroneous navigation information. Information to the ADI is provided by two redundant vertical gyros and various navigation equipment. During an AMCM mission the horizontal and vertical command bars are used to indicate track deviation and speed deviation respectively. A left deflection of the track deviation bar from the center of the ADI indicates that the helicopter is right of the desired AMCM track and visa versa for

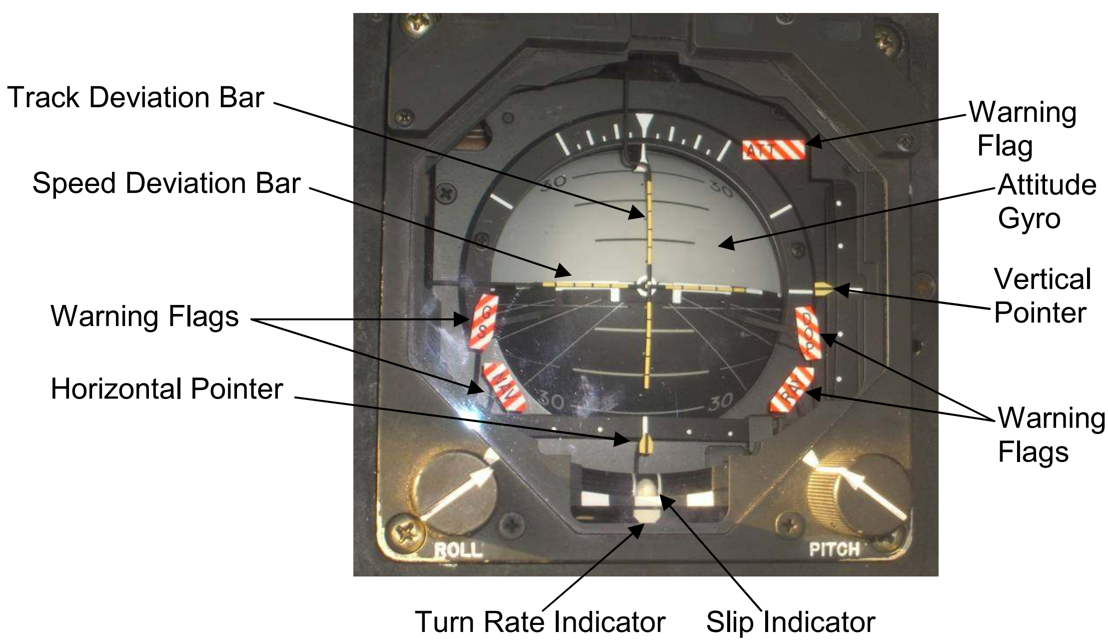

Figure 4. Attitude Direction Indicator.

Source: LCDR Jeff Farlin, Helicopter Mine Countermeasures Squadron FOURTEEN (HM-14), Norfolk, VA, 2008.

right deflection. An upwards deflection of the speed deviation bar from the center of the ADI indicates the aircraft is flying slower than the desired speed. A downwards deflection indicates the aircraft is flying faster than the desired speed. The command bars indicate to the pilot the direction he needs to fly towards. For example, if the deviation bars are displaced up and to the right, this would indicate that the aircraft is left of track and slower than the desired speed. The pilot would be required to make a cyclic flight control input up and right in order to bring the deviation bars back to center. The vertical pointer located on the right side of the ADI provides relative aircraft position longitudinally within a minefield. The horizontal pointer located along the bottom of the ADI provides relative aircraft position laterally. For example, as shown in Figure 4, if both the vertical and horizontal pointers are at the center of their respective scales, this would indicate that the aircraft is located at the center, longitudinally and laterally, of the minefield.

The Horizontal Situation Indicator uses navigation information from several sources to display heading, course, course deviation, glide slope, range and bearing to a navigational aid (NAVAID) as well as warning flags, which provide crew alerting similar to those of the ADI. Information to both HSI's is provided by a single Attitude and Heading Reference System (AHRS) and various navigation subsystems. During an AMCM mission the HSI's primary purpose is to provide heading information and minefield orientation to the pilots and is shown in Figure 5. Heading information is located at the 12 o’clock

position beneath the lubber line. The course set pointer is adjusted by the pilot, via the course set knob, to align with the direction of the minefield. For example, from Figure 5, the aircraft heading would be North and the minefield would be oriented on a 255/075 heading.

The Tension and Skew Indicator (TSI) is one of the most utilized instruments during an AMCM mission and is shown in Figure 6. The monochromatic, liquid crystal display TSI provides the necessary tension and skew information of the tow cable required to keep the AMCM weapon system within prescribed safety limits. Tension is the amount of load, measured in pounds, which the tow cable is experiencing. Factors that effect tension are ground speed, device depth, and water current. Tension is displayed both graphically and in digital read out. Two segmented arches can graphically display tensions from 0-40,000 lbs. Skew, measured in degrees left or right, is the angle between the cable and the longitudinal axis of the aircraft. Factors affecting skew are aircraft heading, water current, and device hydrodynamics. Skew is displayed graphically via three white “chicklets” that slide left or right on a horizontal scale. Tension and skew information come from load cells and rotary transformers attached to the tow boom within the aircraft cabin.

Two RADALT’s, located on the instrument panel, provide vital altitude information to the pilots while conducting the low altitude AMCM mission. The RADALT provides altitudes above ground level (AGL) from 0-5000 ft. A low

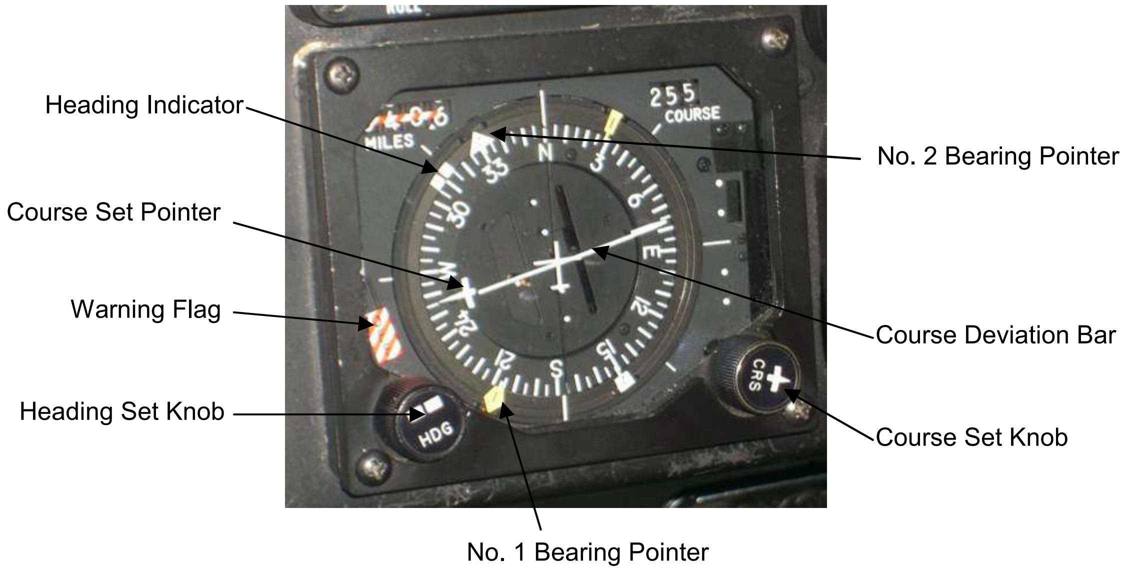

Figure 5. Horizontal Situation Indicator.

Source: LCDR Jeff Farlin, Airborne Mine Counter Measures Weapon Systems Training School (AWSTS), Norfolk, VA, 2007.

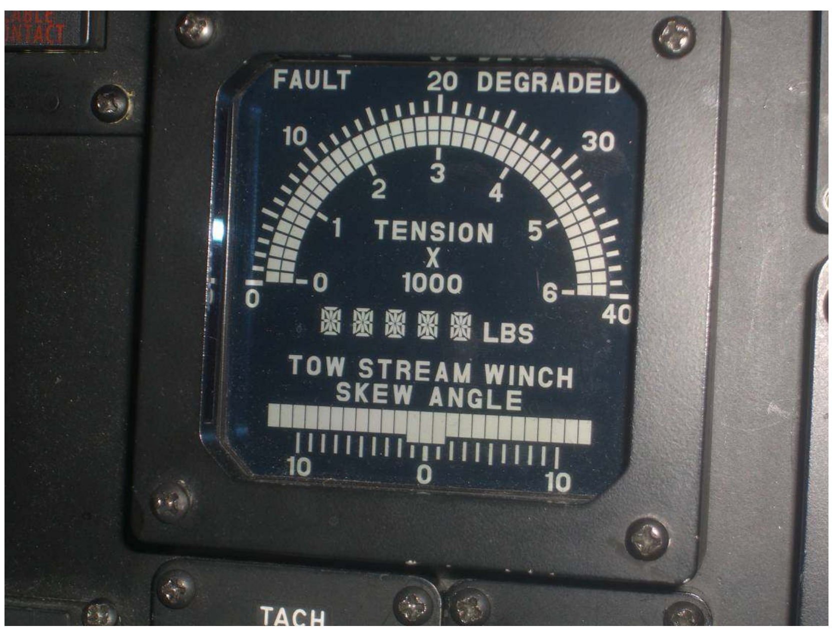

Figure 6. Tension and Skew Indicator with all Indicators Illuminated.

Source: LCDR Jeff Farlin, Airborne Mine Counter Measures Weapon Systems Training School (AWSTS), Norfolk, VA, 2008.

altitude warning “bug” on the RADALT can be manually adjusted by the pilot to a desired altitude which illuminates the “LOW” light should the aircraft descend below the selected altitude. The automatic flight control system (AFCS) of the MH-53E incorporates a RADALT HOLD feature which will automatically provide collective inputs in order to maintain a desired altitude. An illuminated RADALT light on the AFCS panel on the lower console indicates that the RADALT is engaged. This feature is commonly utilized during an AMCM mission. A picture of the RADALT is presented in Figure 7.

The GSDA indicator provides magnitude and direction of drift via the Doppler radar. There are two GSDA’s located on the instrument panel. During the AMCM mission the GSDA is the primary instrument for ground speed (which is directly proportional to cable tension). Drift angle is mainly utilized during the

Figure 7. Radar Altimeter.

Source: LCDR Jeff Farlin, Airborne Mine Counter Measures Weapon Systems Training School (AWSTS), Norfolk, VA, 2007.

stream and recovery phases of the mission where the aircraft needs to be in a hover or at a very slow forward drift. Typically at low altitudes and airspeeds, such as during the AMCM mission, the helicopter pilot will rely on an outside scan to determine aircraft drift. Hovering over water, however, makes this technique near impossible due to the featureless characteristics of the water surface as well as the apparent drift inducing effect of rotor downwash. The drift information the GSDA provides is crucial in order for the pilot to maintain a steady platform while crewman in the cabin stream and recover the AMCM equipment. A picture of the GSDA is presented in Figure 8.

The MK-108 is the primary pilot interface, via an LCD screen and keypad, for setting up and executing the AMCM mission. Information to the MK-108 is

Figure 8. Groundspeed and Drift Angle Indicator.

Source: LCDR Jeff Farlin, Airborne Mine Counter Measures Weapon Systems Training School (AWSTS), Norfolk, VA, 2007.

provided via the MK-86 navigation director and Global Positioning System (GPS). The MK-86 processes GPS information in conjunction with mission data loaded via a flashcard and presents that information to the cockpit through the MK-108. While the MK-108 provides many functions, the focus of this paper will concentrate on those required for an AMCM tow mission (Figure 9). Primarily they are track number, track deviation, distance to the end of the track, time to the end of the track, track course, speed over ground, and display scale. Track deviation, measured in yards, is presented graphically as well as through a digital readout. The graphical representation shows the helicopter at the center of the display with the track bar moving left or right along a horizontal scale. The track bar left of the aircraft (or aircraft right of the track bar) indicates that the helicopter

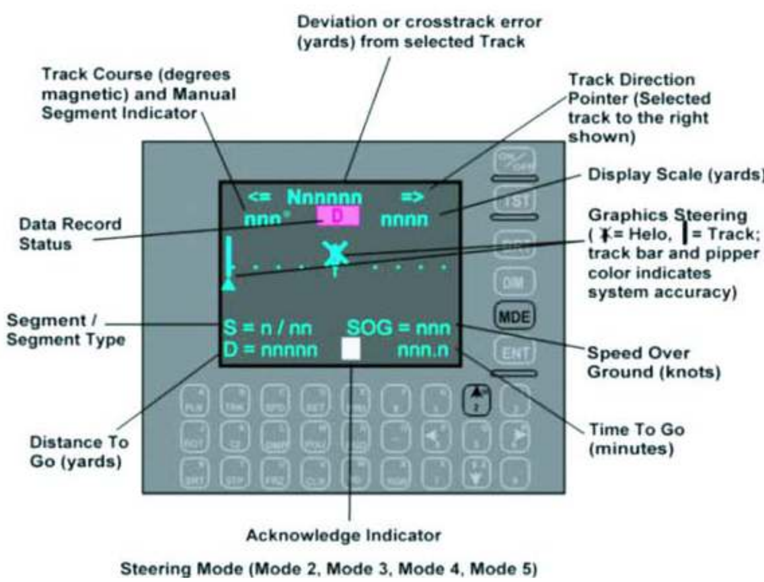

Figure 9. MK-108 Mod 0 Display Unit.

Source: Naval Air Systems Command, *Draft MH-53E Naval Aviation Technical Information Product (NATIP), NTRP 3-22.4-MH53E,* Airworthiness Office (AIR-4.0P) NATIP Division, Patuxent River, MD, 2006.

is right of track (and visa versa). The aircraft is on track when the track bar is directly beneath the aircraft and the digital readout of track deviation is zero. The track bar also indicates, through color, the measure of GPS accuracy called Figure of Merit (FOM). When the FOM is less than 2 the track bar is green. When the FOM is greater than or equal to 2 the track bar is yellow. At FOM's greater than 3 the track bar turns red.

1.2.3 CNS/ATM Cockpit

An artist's conception of the glass cockpit is presented in Figure 10. As is evident, considerable changes were made to the glass cockpit from the legacy cockpit. The basic premise going into the design of the glass cockpit was "to do no harm". This meant that the current functionality that exists in the legacy cockpit must also exist in the glass cockpit. Improvements to that functionality through better use of controls and displays or new functions were also realized. AMCM specific controls and displays in the glass cockpit are the Tow Tension and Skew Indicator (TOW:TSI), the Tow Geographical Situation (TOW:GEOSIT) display, and the CDU-7000 control panel. As of the writing of this paper, there is no CNS/ATM equipped aircraft; however, the first H-53 helicopter is currently undergoing modification. A CNS/ATM prototype lab has been assembled, though, as a test bed to evaluate the proposed cockpit layout (see Figure 11). AMCM controls and displays are displayed via five 6x8" multi-function displays (MFD's) located on the instrument panel. AMCM information is displayed using

Figure 10. MH-53E CNS/ATM Cockpit.

Source: Courtesy, Mr. Ken Hecker, Rockwell Collins, Received June 2007.

Figure 11. CNS/ATM Prototype Lab.

Source: LCDR Jeff Farlin, H-53 Heavy Lift Helicopters Program Office (PMA-261), Patuxent River, MD, 2007.

half-page or full-page format. Half-page means that only half of the MFD is required to display the information. Full-page uses the entire MFD. The TOW:TSI page utilizes a half-page format while the TOW:GEOSIT utilizes a full-page format. The TOW:TSI and TOW:GEOSIT pages can be displayed on any one of the five MFD's based on pilot preference. Execution of mission tasks can also be accomplished via the CDU-7000 located on the lower console.

The TOW:TSI page, pictured in Figure 12, provides all the necessary tow information in one concise area. The TOW:TSI display, similar to the legacy TSI, shows tension and skew information as well as load source. In addition, the TOW:TSI display provides track deviation via a vertical deviation bar and speed deviation via a horizontal deviation bar. Similar to the legacy ADI the pilot flies to

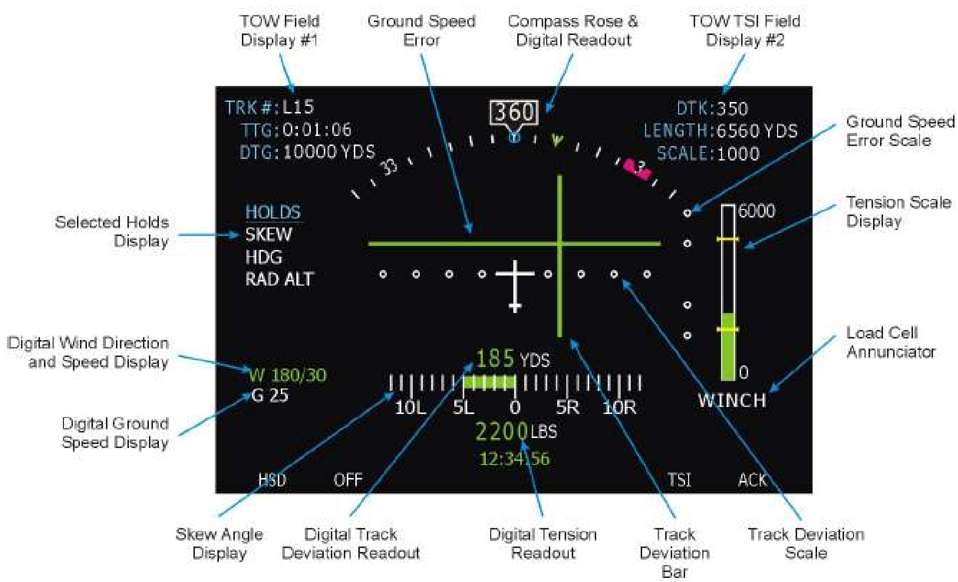

Figure 12. TOW:TSI Format.

Source: Rockwell Collins, *United States Navy (USN) CH-53E/MH-53E Communication, Navigation, and Surveillance / Air Traffic Management (CNS/ATM) Upgrade Program Flight2™ Human Machine Interface Design Document (HMIDD), Draft D*, Rockwell Collins, Cedar Rapids, IA, 2007.

the deviation bars in order to bring them to center. Track and speed deviation is zero when the deviation bars are centered. Track deviation is also displayed through a digital readout located on the bottom center of the display. The color of the vertical and horizontal deviation bars indicate the current FOM. FOM is measured on a scale from 1-8 with 1 being the best (least navigation error) and 8 being the worst (most navigation error). At an FOM of 1 the deviation bars are green. At FOM 2 the deviation bars change to yellow and FOM 3 change to red. Tension is displayed both graphically via a vertical “tape” on the right side of the display and through a digital readout located directly below the skew scale. The tension scale display changes colors from green to yellow to red under certain tension situations. The yellow “dogbone” indicators on the tension skew display are pilot adjustable hi-set and low-set tensions. When tension exceeds the hi-set or is less than the low-set the tape turns yellow. The tape turns red when tension exceeds the auto-release setting (typically 12,500 lbs). As with the legacy TSI the source for tension information comes from load cells located on the tow boom within the cabin.

The skew angle scale is located at the bottom center of the display and is similar to the legacy skew angle scale except that instead of the three “chicklet” indicator there is a skew “tape” that fills in the scale as skew changes. The skew tape, as with tension, changes colors under certain skew conditions. The tape is green at skews from 0-8 degrees, yellow at 8-11 degrees and red at > 11

degrees. As with the legacy TSI the source for skew information comes from rotary transformers located on the tow boom within the cabin.

On the bottom left of the TOW:TSI display an indication of winds and ground speed is presented. A readout of “W 180/30” indicates that the winds are from 180^{o} at 30 kts. A readout of “G 150” means that the ground speed is 150 kts. Source of information for winds and ground speed comes from an Embedded Global Position System/Inertial Navigation Unit (EGI).

A selected holds table is displayed on the left side of the display. This alerts the pilot as to which AFCS hold functions are engaged. There are five possibilities: skew hold, ground speed hold, tension hold, heading hold and RADALT hold.

Mine field navigation data is provided in Tow Field Display #1 (upper left) and Tow Field Display #2 (upper right). Tow Field Display #1 indicates the current track selected as well as distance and time to go to the current waypoint. When a track is selected a GPS waypoint is inserted at the beginning and end of the track. Normally, the pilot would select a track outside of the mine field and navigation is then provided to the beginning waypoint. Once that waypoint is captured (aircraft flies within a certain capture radius) then the beginning waypoint goes away and navigation is provide to the end waypoint and so on. Tow Field Display #2 provides the desired track (DTK), the length of the minefield and the selected scale used for track deviation display. Between the two Tow Field Displays there is a compass rose and digital readout which indicate the

current heading of the aircraft. There are three unique indicators on the compass rose that provide additional navigation information. The green carrot or “v” indicates the heading to the current waypoint. The blue circle is an indication of the wind corrected heading to the current waypoint. Finally, the broken magenta box is a pilot selectable heading reference.

The CDU-7000, shown in Figure 13, is the primary control interface between the pilot and navigation, communication, Identification Friend or Foe (IFF), data link, system configuration and mission functions. The CDU-7000 is divided between labeled keys and soft keys. The labeled keys include the alphanumeric keyboard as well as main subsystem keys located across the top of the CDU-7000. The soft keys or line select keys (LSK) are those labeled with a right or left pointing white arrow. The subsystem keys are used to select a

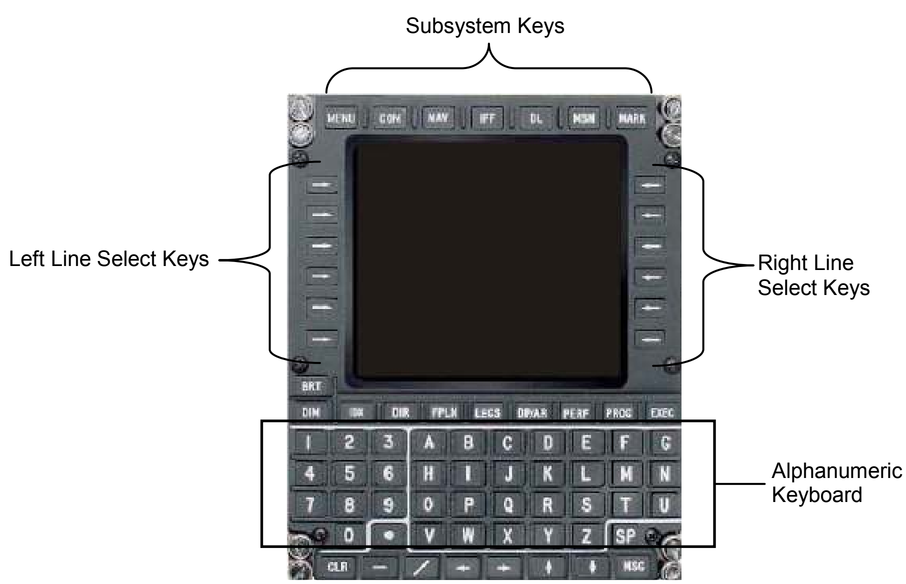

Figure 13. CDU-7000 Control Panel.

Source: Ibid.

specific subsystem while the LSK’s are used to navigate the page layers within each subsystem. While the CDU-7000 provides many functions this paper will only concentrate on those that are utilized while executing an AMCM mission. AMCM mission functions are accessed by pressing the Mission (MSN) subsystem key followed by pressing the TOW LSK which brings up the Tow Control Page. From the Tow Control Page the pilot sets-up and runs the AMCM mission. The pilot does so by selecting the MCM plan to be executed, the device that will be towed, reference speed, track extension, scale and desired track.

1.3 Airborne Mine Countermeasures (AMCM) Mission

The United States Navy is one of only two countries in the world (Japan being the other) that conduct the AMCM mission. The primary mission of the MH-53E Sea Dragon is to conduct this highly unique mission. The MH-53E does so by employing a variety of weapons systems to search, detect, localize, and in some cases, neutralize underwater mines. Each weapon system is placed in the water and is connected to the helicopter via a tow cable. The helicopter can then pull or “tow” the system through the water searching for mines.

1.3.1 AMCM Weapons Systems

Currently there are five weapons systems that the MH-53E routinely employs in order to carry out its primary mission. They are the MK-103 mechanical minesweeping system, the MK-104 acoustic influence system, the MK-105 magnetic influence system, the AN/SPU-1W Magnetic Orange Pipe

(MOP) magnetic influence system, and the AN/AQS-24 mine hunting system. Pictures of all five systems are presented in the Appendix, Figures A-30 to A-34. Both the MOP and MK-105 generate a magnetic field that is designed to detonate a magnetic influence mine while the MK-104 generates an acoustic field which is designed to detonate an acoustic influence mine. The MK-104 can be connected to the MK-105 (called the MK-106) to create a combined magnetic/acoustic field. The purpose of magnetic or acoustic field generating devices is to produce a magnetic and/or acoustic environment similar to a surface ship thus tricking the mine into thinking that a surface ship, a mine's primary target, is passing overhead. The MK-103 mechanical minesweeping system is a complex series of sweep cables with explosive cutters designed to cut the cable of the moored mine. A moored mine (Appendix, Figure A-35) is a mine that is typically positioned just below the surface and is held in place with a cable attached to an anchor on the sea floor as opposed to a bottom mine (Appendix, Figure A-36) which simply rests on the "bottom" of the sea floor. The AN/AQS-24 mine hunting system is a towed sonar device that searches for bottom mines primarily but can also detect moored mines in the water volume under certain conditions.

1.3.2 Mission Profile

In order to understand and evaluate the implications of the glass cockpit AMCM controls and displays as compared to legacy AMCM controls and displays an understanding of the AMCM mission is required. There are seven different

phases that comprise the AMCM mission. They are pre-flight, take-off and transit, stream, tow, recovery, transit and land, and post-flight. A graphical representation of the AMCM mission is presented in Figure A-37, in the Appendix. During the first three phases the aircrew receives the mission tasking, pre-flights the aircraft, transits to the minefield, and streams the weapon system, also known as the “device”. Once the device has been successfully streamed into the water the towing phase begins. The focus of this paper will be centered on those functions that occur during the towing phase because it is during this phase that the aforementioned AMCM controls and displays are most utilized. The AMCM pilot will use the tension and skew indications to maintain the device within prescribed limits. The limits on tension will depend on many factors to include device used, speed, and depth. The desired skew angle, with one exception, the MK-104, is always 0^{o}. During the tow phase the aircraft flies up and down pre-determined tracks within a rectangular shaped mine field. Tracks are measured in yards from the centerline (also referred to as track 0) of the minefield to the left or right edge of the field. In Figure 14, an example minefield is presented that has a width of 1000 yds, length of 2000 yds, and three tracks (-250, 0, 250). The centerline, or track 0, is labeled A-B. The “negative” side of the field is the side to the left of centerline as looking from A to B. The “positive” side would then be to the right of centerline as looking from A to B. The pilot will maintain the desired track and speed via the track and speed deviation bars. While flying down a track, distance-to-go and time-to-go is used to determine

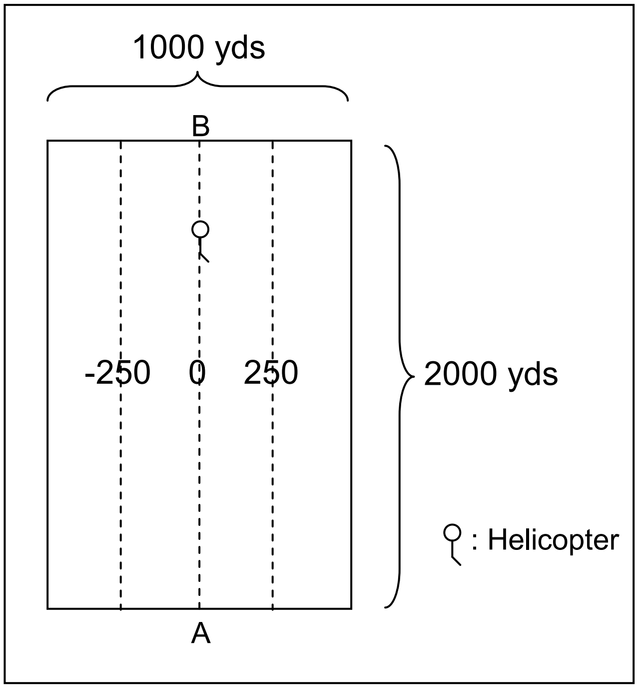

Figure 14. Example of a Minefield.

Source: Created by the author using Microsoft Office PowerPoint 2003, 2008.

when the aircraft is approaching the end of the track. When the aircraft reaches the end of the current track the pilot will then select the next desired track. This process continues until all assigned tracks are completed. Tow speeds can be anywhere between 12-25 KGS at an altitude of approximately 125 ft AGL. To assist the pilots in maintaining altitude, the RADALT hold feature is always used. Any of the other tow coupler features (skew hold, heading hold, tension hold, and groundspeed hold) may also be used. Duration of the tow phase is strictly dependant on fuel burn rates, fuel load and amount of fuel to recover the device and transit back to home base. On average, however, tow time is typically between 2 to 2 ½ hours. Once towing is complete, the remaining three phases of

flight are executed. The device is recovered, the aircraft transits back to home base, and a post mission debriefing is conducted.

SECTION II: MATERIALS AND METHODS

2.1 Test Method and Procedures

In order to assess the capability of one cockpit configuration verses another in terms of performing the AMCM mission five criteria related to human factors concerns when using AMCM controls and displays were evaluated. They were physical characteristics, location and grouping, labeling, physical workload, and mental workload. All tests were conducted from the right seat. Table A-7, in the Appendix, presents the tests and test procedures used to conduct this evaluation.

The physical characteristics of the tension display and skew display were qualitatively evaluated for their salient features such as location, labeling, color and shape. Tension display, track deviation, coupler holds, and the display of minefield data were evaluated for their location and grouping within both cockpits. To this end, eye distance and head azimuth to the aforementioned displays were measured. Additionally, the evaluator's anthropometrics were measured since eye distance and head azimuth to the relevant AMCM displays was directly related to the anthropometrics of the evaluator. Since the author was, for the most part, the sole evaluator of this crew station design, his anthropometric characteristics had to be considered in relation to the 5^{th} and 95^{th} percentile anthropometric data bases. Labeling of the skew display and DTG display was evaluated based on the arrangement of scale graduation marks and the means by which the units of measure were displayed.

Physical and mental workloads were evaluated for their obvious impacts on executing the AMCM mission. Physical workload was measured by counting the number of key presses required to select a programmed or manual track and was conducted as a single task. The accessibility of the controls required to select a track was also evaluated by defining which of the three functional reach zones those controls fell within. For the accessibility test, three evaluators were utilized to cover a wide range of functional fingertip reaches. The evaluator's anthropometrics were required since the location of the functional reach zones were dependant on the evaluator's measurements. A limited, qualitative evaluation of mental workload was also conducted. Specifically, an assessment of whether or not mental calculations were required to interpret Distance-To-Go information was evaluated.

Where applicable, the five characteristics were also evaluated using the Department of Defense Design Criteria Standard: Human Engineering, MIL-STD-1472F[8] and the Department of Defense Handbook for Human Engineering Design Guidelines, MIL-HDBK-759C[9]. The scope of MIL-STD-1472 is to "*establish general human engineering design criteria for military systems, subsystems, equipment and facilities*."[8] MIL-STD-1472 criteria that was evaluated against was coding of the visual displays, location and arrangement of displays, scale indicators, and information format. Specifically, tension and skew displays were evaluated against MIL-STD-1472 standards for flash coding. The ADI, TSI, MK-108, GSDA, and the TOW:TSI displays were evaluated for their

location and arrangement. The skew display was evaluated for its indication of scale and the display of DTG was evaluated for its information format. MIL-HDBK-759 is intended to be used as a companion document to MIL-STD-1472 and provides further human engineering design guidelines and reference data.

2.2 Anthropometric Measurements

Of the 203 anthropometric measurements of the human body, seven were considered the most important with regards to aircrew station design. These were total sitting height, sitting eye height, sitting shoulder (acromiale) height, bideltoid diameter (shoulder width), functional reach (grasp between thumb and forefinger), fingertip reach ("pushbutton" reach with extended forefinger), and buttocks-to-knee length (sitting).[2] These seven measurements were important when assessing the location and accessibility of AMCM controls and displays. For example, the location of the ADI relative to the evaluator was a function of the evaluator's sitting height, sitting eye height and buttocks-to-knee length. AMCM controls required to select a track was primarily dependant on the evaluator's fingertip reach but shoulder height, shoulder width, and functional reach also played a role. Table 1 shows the seven anthropometric measurements for the male evaluator with their associated percentile and their relationship to the 5th, 50th, and 95th percentile male and female. Generally speaking, cockpits are designed to accommodate individuals within the 5th-95th percentile range.[8] The majority of the tests were conducted with the male evaluator described in Table 1; however, for the accessibility test of

Table 1: Comparison of Anthropometric Measurements Between the Evaluator and the 5th, 50th, and 95th Percentile Male and Female.

Dimension(1)	Evaluator (cm / %)	5th Percentile (cm)		50th Percentile (cm)		95th Percentile (cm)	
	Male	Male	Female	Male	Female	Male	Female
Functional Reach	83.8/83rd	73.9	67.7	80	73.4	86.7	79.7
Bideltoid Breadth	49.8/60th	45.0	39.7	49.1	43.1	53.5	47.2
Sitting Height	95.5/87th	85.5	79.5	91.4	85.1	97.2	91.0
Sitting Eye Height	81.1/71st	73.5	68.5	79.2	73.8	84.8	79.4
Acromiale Height, Sitting	62.6/83rd	54.9	50.9	59.8	55.5	64.6	60.4
Buttock-Knee Length	60.4/35th	56.9	54.2	61.5	58.8	66.7	64.0
Shoulder-to-Fingertip Reach	85.1/93rd	72.9	66.2	78.8	72.3	85.6	78.8

Notes:
(1) Measurements from 1988 Army Survey Dataset

Source: Department of Defense Handbook, *Anthropometry of U.S. Military Personnel, DOD-HDBK-743A*, U.S. Army Natick Research, Development and Engineering Center, Natick, MA, 1991.

the MK-108 and CDU-7000 two female evaluators with finger-tip reaches in the 5th percentile were also utilized. For the two female evaluators the fingertip reach was 66.8 cm/5th percentile and 66.5 cm/5th percentile respectively. The 66.8 cm female was used to evaluate the legacy cockpit while the 66.5 cm female was used to evaluate the glass cockpit. One female evaluator was used to evaluate the CDU-7000 in the glass cockpit and the other female evaluator was used to evaluate the MK-108 in the legacy cockpit. The same male evaluator was used for both the glass and legacy cockpits. The anthropometric data in Table 1 are provided to show a comparison between the evaluator and the full spectrum of a population from the 1988 Army Survey Dataset. The 1988 Army Survey Data set was a survey where 132 measurements were taken from 5499 males and 3485 females and then characterized in terms of percentiles. Percentiles are used to compare an individual to a large group of individuals or a population. For example, the evaluator had a fingertip reach of 85.1 cm which placed him at the 93rd percentile. This means that the evaluator's functional reach was greater than 93% of the population or less than 7% of the population. This is important to note because while an individual with a 93rd percentile functional reach may be able to reach and actuate a certain control, someone in the 50th percentile may not. It should also be noted, however, that most cockpits have an adjustable seat and/or pedals which, theoretically, can be adjusted to accommodate for different size pilots. The evaluator's measurements were made with the evaluator sitting on an anthropometric chair with the exception of functional

reach, fingertip reach, and bideltoid breadth in which the evaluator was standing. Sitting measurements were taken with the evaluator sitting straight up with his back against a wall and head level, feet were flat on the floor with knees together and bent at right angles. Standing measurements were taken with the subject standing erect, back against the wall, head level and heels together. All measurements were taken to the nearest 1/10th of a centimeter. Sections 2.2.1-2.2.7 describes how each of the measurements were taken and comes directly from the *Anthropometry of U.S. Military Personnel Handbook, DOD-HDBK-743A*.[10] A graphical representation of the seven anthropometric measurements is presented in the Appendix, Figures A-38 to A-43. The numbers illustrated in each of those figures relate to a specific anthropometric dimension and are not themselves a measurement of the evaluator.

2.2.1 Functional Reach

The horizontal distance from the wall to the tip of the thumb was measured with the subject's shoulders against the wall with the arm extended forward and the index finger touching the tip of the thumb (72, Figure A-38)

2.2.2 Bideltoid (Shoulder) Breadth

Bideltoid breadth was measured as the horizontal distance across the upper arms between the maximum bulges of the deltoid muscles with the arms hanging and relaxed (151, Figure A-39).

2.2.3 Sitting Eye Height

Sitting eye height was the vertical distance from the sitting surface to the outer corner of the eye (ectocanthus), measured with the subject sitting (61, Figure A-40).

2.2.4 Sitting Height

Sitting height was the vertical distance from the sitting surface to the top of the head, measured with the subject sitting (157, Figure A-41).

2.2.5 Acromiale (Shoulder) Height

Acromiale height was the vertical distance from the sitting surface to the point of the shoulder (acromion), measured with the subject sitting (155, Figure A-41).

2.2.6 Buttock-to-Knee Length

Buttock-to-knee length was the horizontal distance from the back of the buttock to the front of the knee, measured with the subject sitting (32, Figure A-42).

2.2.7 Shoulder-to-Fingertip Length

Shoulder-to-fingertip length was the length of the arm and hand from the point of the shoulder (acromion) to the tip of the middle finger (dactylion), measured with the arm hanging and relaxed (154, Figure A-43).

2.3 Legacy Cockpit Measurements

The evaluation of legacy AMCM controls and displays was conducted in the MH-53E simulator and an MH-53E helicopter located at the Norfolk Naval Base in Norfolk, VA. Measurements of the legacy cockpit were required to define the seat position as this directly affected the eye distance, head azimuth, and accessibility to AMCM controls and displays. Figure 15 is a picture illustrating relevant legacy cockpit dimensions**.** The evaluation was conducted from the pilot station (right seat) with the seat adjusted to match the dimensions of the CNS/ATM Prototype lab. Matching the legacy seat position to that of the prototype lab was required to make a fair comparison between the two cockpits since the seat in the prototype lab was not adjustable in any axis. Placing the legacy seat in the correct position was accomplished by adjusting the seats vertical axis to full down and adjusting the horizontal axis by locking the seat into the fourth detent from the full aft position. At this position the evaluator's eyepoint was 2.25 cm below the design eye point (DEP). The evaluator was wearing normal summer flight clothing and equipment as presented in Table A-8 and Figures A-44 and A-45 in the Appendix. The seat belt and safety harness was fastened with the inertial reel locked when defining the accessibility of AMCM controls located within Reach Zones 1 and 2. The seat belt and safety harness was fastened with the inertial reel unlocked when defining the accessibility of controls located within Reach Zone 3. All eye distance and

Figure 15. Legacy Cockpit Dimensions.

Source: LCDR Jeff Farlin, Helicopter Mine Countermeasures Squadron FOURTEEN, Norfolk, VA, 2008.

grouping measurements were taken to the nearest 0.0625 inch using a tape ruler with 0.0625 inch accuracy. Measurements were rounded to the nearest inch or half-inch. Changes in head azimuth required to view an AMCM control or display were measured using a protractor with 1° accuracy.

2.4 CNS/ATM Cockpit Measurements

The physical evaluation of glass cockpit AMCM controls and displays was conducted at the H-53 CNS/ATM Prototype lab located at Naval Air Station Patuxent River, MD. Figure 16 is a picture illustrating relevant glass cockpit dimensions. The evaluation was conducted from the pilot station (right seat) which was not adjustable in any axis. This placed the evaluator's eyepoint at a position 2.25 cm below the DEP. Measurements of the glass cockpit were required to define the seat position as this directly affected the eye distance, head azimuth, and accessibility to AMCM controls and displays. While the pilot seat and flight controls were not exact representations of the MH-53E, the location of the seat and flight controls with respect to the center console and instrument panel was considered representative. It should also be noted that the CDU-7000 was not the real CDU-7000, but rather a touch screen CDU-7000 that had the same measurements and location as the real CDU-7000. The instrument panel was the same panel that is installed on the current MH-53E helicopter. The evaluator was wearing the same flight gear as in the legacy cockpit. Angle and distance measurements were conducted using the same measuring equipment described in the previous section.

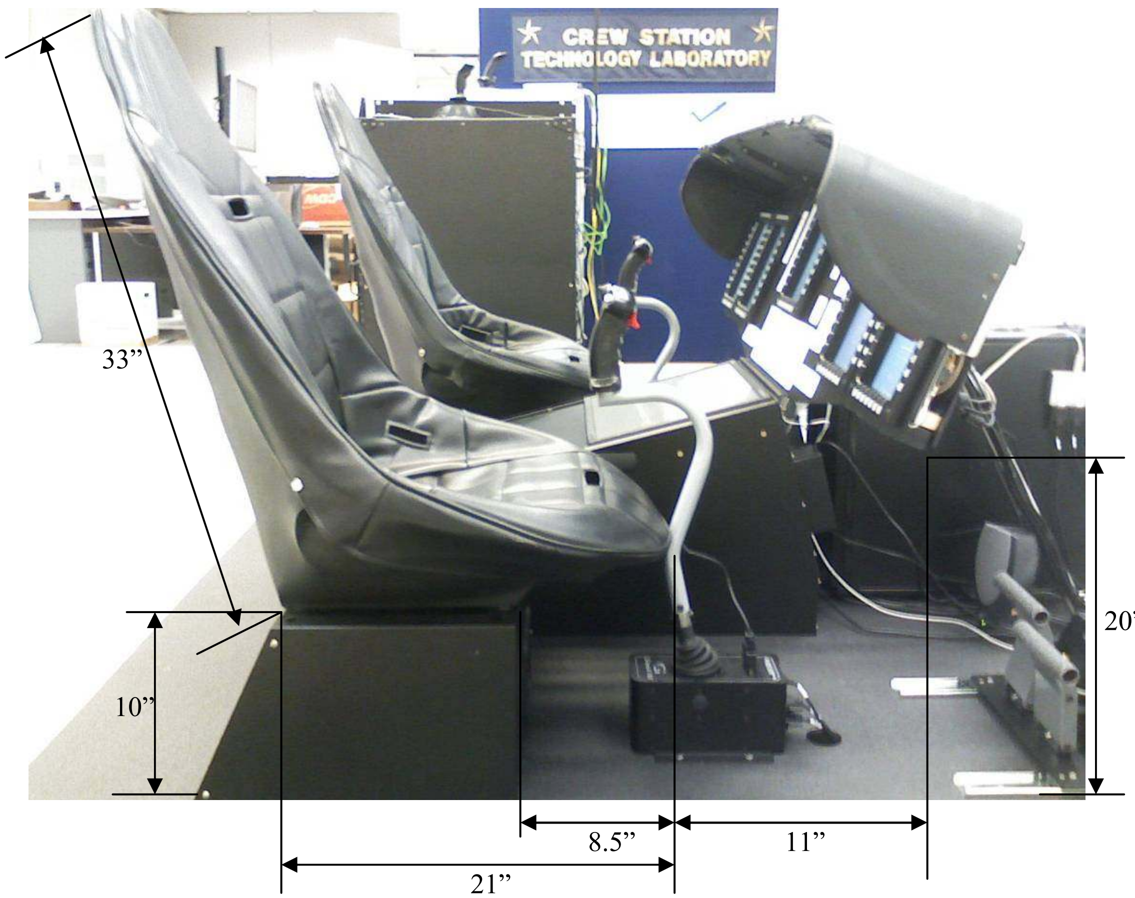

Figure 16. CNS/ATM Cockpit Dimensions.

Source: LCDR Jeff Farlin, H-53 Heavy Lift Helicopters Program Office (PMA-261), Patuxent River, MD, 2007

2.5 Workload Measurements

A limited analysis of mental workload and physical workload was evaluated. Mental workload was qualitatively evaluated by assessing whether or not mental calculations were required to interpret Distance-To-Go information. Physical workload was quantitatively evaluated by counting the number of button pushes required to select a programmed or manual track. Physical workload was also evaluated by the amount of physical effort required by the operator to reach the controls required to select a programmed or manual track on the MK-108 or CDU-7000 and was conducted from the right seat. For this test, three evaluators (one male, two female) were used in order to gather test data for a wide range of shoulder-to-fingertip reach's. The male evaluator's finger tip reach was in the 93rd percentile while the female evaluators were both in the 5th percentiles. As previously discussed, the seat in the legacy cockpit was adjusted to match the location of the fixed seat in the prototype lab in order to provide a fair comparison between the two cockpits. Both female evaluators commented that if they could adjust the seat, they would raise it approximately 0.5 to 1 inch. During the evaluation of the legacy cockpit the evaluator was allowed to adjust her seat after the equivalent prototype lab seat position was evaluated. She did so by raising the seat by one detent from full down which equated to about 1 inch. It was determined that the results from the functional reach test were the same between the prototype lab seat position and the preferred seat position.

The ability to reach AMCM controls was characterized by Reach Zones.

Functional Reach Zones are defined by MIL-STD-1333B, *Aircrew Station Geometry for Military Aircraft*[4] and are:

> Reach Zone 1: Restraint Harness Locked - Functional Reach. This zone includes the area that can be functionally reached and actuated by any crewmember of the population defined by the acquiring activity when located at the appropriate design eye position fully restrained and equipped without stretch of arm or shoulder muscles.
>
> Reach Zone 2: Restraint Harness Locked - Maximum Functional Reach. This zone includes the area that can be functionally reached and actuated by any crewmember of the population defined by the acquiring activity when located at the appropriate design eye position fully restrained and equipped with maximum stretch of shoulder and arm muscles.
>
> Reach Zone 3: Restraint Harness Unlocked - Maximum Functional Reach. This zone includes the area that can be functionally reached and actuated by any crewmember of the population defined by the acquiring activity when located at the appropriate design eye position with the shoulder restraint fully extended and the arms stretched full length.

A graphical representation of Functional Reach Zones is presented in Figure 17.

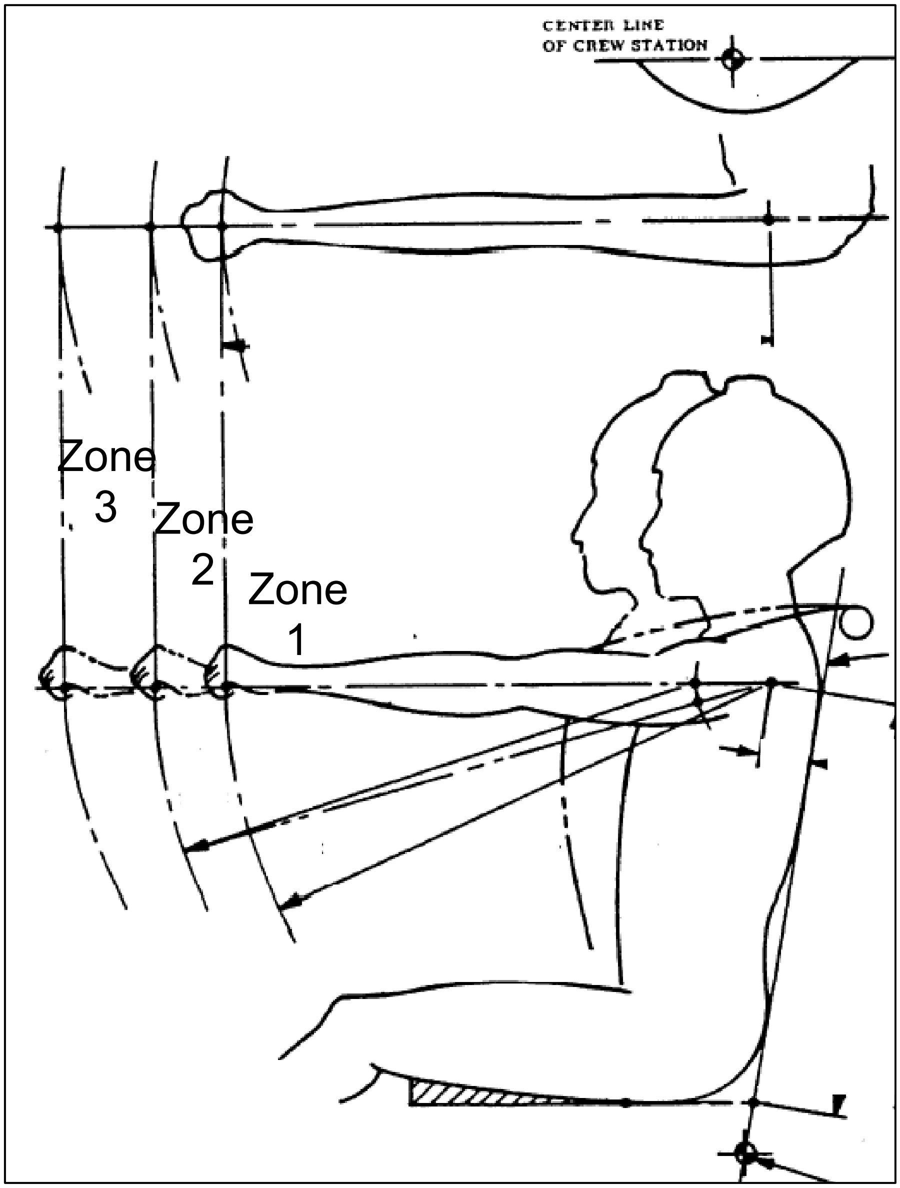

Figure 17. Functional Reach Zones.

Source: Military Standard, *Aircrew Station Geometry for Military Aircraft, MIL-STD-1333B,* Naval Air Engineering Center, Lakehurst, NJ, 1987.

SECTION III: RESULTS AND DISCUSSION

3.1 Physical Characteristics of AMCM Displays

The salience of control and display cues were important in that critical AMCM information is presented to the pilot in such a way that it stands out from other cues. A well designed cue not only captures the pilot's attention, but can also provide an indication as to what action the pilot should take. "*The display must not only present the information—it must present it in a way as to help the brain in processing its task.*"[11] Characteristics that made an object salient were location, size, and color, to name a few. The AMCM cues that were evaluated for their salient features were tension and skew display since they were considered two of the most utilized displays during an AMCM mission.

3.1.1 Tension Display

As described in Section 1, the tension display in the glass cockpit was located on the right side of the TOW:TSI page and is a color vertical gauge. The display of tension in the legacy cockpit was located on the TSI and was a monochromatic round gauge. Both configurations also provided a digital readout of tension. While both tension indications were displayed via glass displays there were significant differences between the two, color and shape being the most obvious. In the glass cockpit configuration, tension (both the vertical display and digital readout) was colored green, yellow, or red depending on the amount of tension realized. The green/yellow/red format was very salient in that most

people understand the meaning of those three colors (most likely due to traffic stoplights). Green indicates that everything is normal, yellow means take caution, and red means warning. With the monochrome design of the legacy tension gauge the advantage of color coding was not possible and, therefore, less salient than the glass cockpit tension gauge for visual display of tension limits. One way that the legacy tension gauge did attempt to increase saliency, however, was by allowing the "TENSION X 1000" to flash when a certain pilot adjustable tension limit was exceeded. Flashing wording does increase saliency; however, this design feature is contrary to MIL-STD-1472 which states that *"Characters that must be read should not flash. Emphasis should be added by an adjacent flashing symbol or flashing background."*[8] As to the format of tension indication (vertical tape vs. round gauge) no definitive data could be found showing which one was more salient. Based on recent, new helicopter platforms (i.e. MH-60S/R, CH-53K), however, the military helicopter community seems to favor vertical gauges over round.

3.1.2 Skew Display

Skew information was provided to the pilot on the TOW:TSI page for the glass cockpit and the TSI gauge for the legacy cockpit. As with the glass cockpit tension display the indication of skew was presented in three colors (green, yellow, and red) and changed depending on the criticality of the skew angle. The legacy skew display was always white regardless of skew angle and, therefore, did not stand out as well as the glass cockpit skew display. In an attempt to

increase the saliency of the skew display, the words “SKEW ANGLE” flashed when a certain skew angle (8^o) was exceeded. As discussed above, however, flashing characters are contrary to the guidelines presented in MIL-STD-1472. Another significant difference between the two skew displays was the way skew was indicated. The glass cockpit skew display utilized a tape format that filled the entire skew scale left or right depending on aircraft skew angle. The skew tape fills the skew scale from “behind” such that the skew scale graduation marks are not masked and allows the pilot to read the value of skew. The legacy cockpit used a three “chicklet” configuration that moved left and right depending on skew angle. In order to determine the actual skew angle the pilot would read the skew graduation mark directly below the center chicklet. The legacy method of skew display does not provide the pilot necessary trending information as well as the glass cockpit method. With the glass cockpit skew display the pilot can better see the skew building as the tape fills to the left or right and thus provides a more salient cue of changing skew angles than the legacy skew gauge.

3.2 Location and Grouping of AMCM Controls and Displays

Just as the physical characteristics of controls and displays affect the saliency of an object so does the location and grouping of objects. Weiner states *“Displays which are sampled most frequently should be located centrally…”*.[12] MIL-STD-1472 states *“Displays used most frequently should be grouped together and placed in the optimum visual zone.”*[8] The “optimum visual zone”, as illustrated in Figure 18, defines the optimum visual cone angle as 30^o.

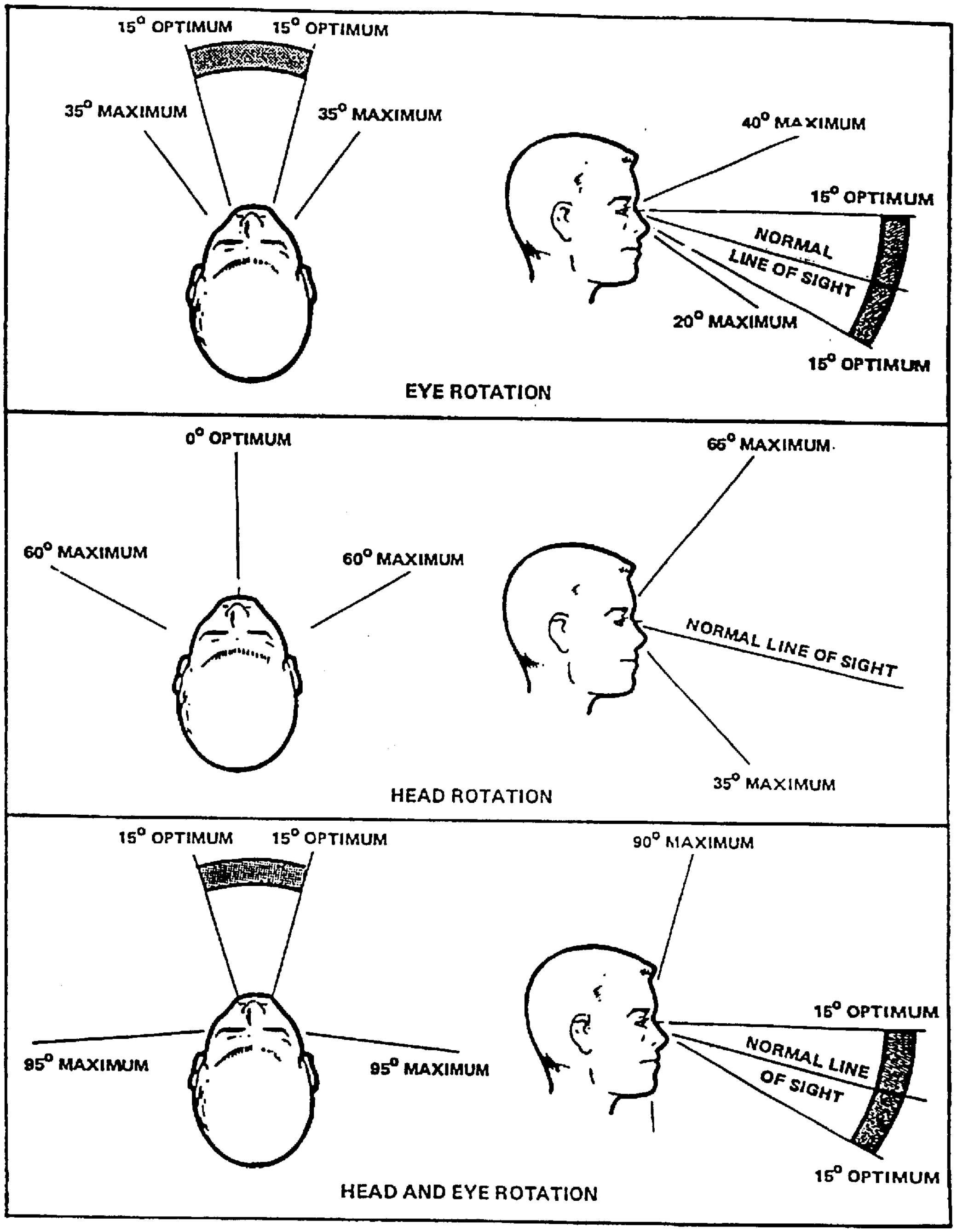

Figure 18. Vertical and Horizontal Visual Fields.

Source: Department of Defense Design Criteria Standard, *Human Engineering, MIL-STD-1472F*, U.S. Army Aviation and Missile Command, Redstone Arsenal, AL, 1999.

An overall assessment of whether or not AMCM displays fell within the optimum cone angle was conducted for both the glass and legacy cockpits. In addition to the overall assessment the following specific AMCM displays were also evaluated for their location, grouping and effect on saliency: track deviation, coupler holds, and mine field data.

3.2.1 Overall Grouping Assessment

In order to determine whether or not the AMCM displays for both the glass and legacy cockpits fell within the optimum cone angle of 30^{o} the relationship of the instruments of interest were referenced to the evaluators normally seated eye position. To determine if AMCM displays were within the optimum cone angle the following equation for a right circular cone was utilized (Figure 19):

$$\theta = 2\tan^{-1}\left(\frac{r}{h}\right) \quad (1)$$

Where: θ is the optimum cone angle (30^{o}).
r is the radius of the optimum visual field.
h is the distance from the pilot's eye to the ADI (28.25") or TSI AC symbol (34").

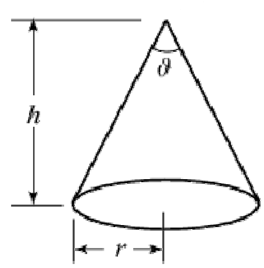

Figure 19. Variables for a Right Circular Cone.

Source: Hilbert, D. and Cohn-Vossen, S., "The Cylinder, the Cone, the Conic Sections, and Their Surfaces of Revolution," *Geometry and the Imagination,* Chelsea, New York, 1999, URL: http://mathworld.wolfram.com/Cone.html [cited 6/17/07].

For the glass cockpit, measurements were taken from the aircraft symbol located on the TOW:TSI page to the tension display, skew display, groundspeed, track deviation, track information and minefield data (see Table 2). For the legacy cockpit, measurements were taken from the ADI to the same aforementioned displays (see Table 3). Measurements were taken from the TOW:TSI aircraft symbol and the ADI because these displays are where the pilot will focus most of his attention. Based on Equation (1) and solving for *r*, the glass displays would have to fall within 9.11 inches of the TSI AC symbol in order to be within the 30^{o} field of view. As shown in Table 2, all pertinent AMCM displays fell well within 9.11 inches. The furthest display was that of groundspeed, which was only 2.875 inches from the TSI AC symbol. For the legacy cockpit, the displays would need to fall within 7.57 inches of the center of the ADI. All of the displays fell within 7.57 inches except for those located on the MK-108 (i.e., track deviation, track information and field information). For those displays that did fall within 7.57 inches, the average distance from the ADI was approximately 5 inches. For the glass cockpit, the average distance from the TSI AC symbol was just over 2.25 inches. The grouping of AMCM displays in the glass cockpit was considered more efficient for conducting the AMCM mission based on the fact that all of the critical AMCM displays fell within the optimum viewing angle and their average distance from the primary line of sight was less than that of the legacy cockpit.

Table 2: Radial Distances From TSI AC Symbol to Primary AMCM Displays.

TSI AC Symbol to AMCM Displays	Distance (in)
Tension #	1.5
Tension bar	2.0625
Skew scale	1.125
Groundspeed #	2.875
Track deviation #	0.875
Track information	2.5
Field information	2.625

Table 3: Radial Distances From ADI to Primary AMCM Displays.

ADI to AMCM Displays	Distance (in)
Tension #	5.25
Tension scale	5.5
Skew scale	5.25
Groundspeed	3.75
Track Deviation #	27
Track Information (DTG) [1]	27.5
Field Information (Field Heading) [2]	27.5

Notes:
(1) Track information (i.e., track #, DTG, TTG) is displayed in three different places on the MK-108. The worst case (i.e., furthest distance) is presented here and is DTG.
(2) Field information (i.e., field heading, track length, scale) is displayed in three different places on the MK-108. The worst case (i.e., furthest distance) is presented here and is field heading.

3.2.2 Track Deviation

Track deviation was displayed via the TOW:TSI page in the glass cockpit and the MK-108 and ADI in the legacy cockpit. The most significant difference that directly affects saliency between the three displays is their location relative to the pilot's viewing angle. The TOW:TSI page could be displayed on the bottom half of any one of the five MFD's located on the instrument panel. In this configuration the pilot could display the TOW:TSI in the most optimal location, presumably on the MFD directly in front of him. The MK-108 on the other hand is located on the top-middle of the lower center console. In order to view track information the pilot must look down and to the center of the cockpit. Measurements of this arrangement are shown in Table 4. While the distance to the MK-108 is 3.5 inches further than the TOW:TSI page the most significant viewing issue was the change in head azimuth required by the pilot to view the displays. With the legacy MK-108 the pilot had to adjust the center of his field of view (FOV) 55^{o} to the left (measurements taken from the right seat). The ADI

Table 4: Eye to Track Deviation Display Measurements

Cockpit	Evaluator Eye Distance to Instrument	Distance (in)	Inclination (deg)	Azimuth (deg)
Glass	Bottom half center of MFD #4	34	35 D	10 R
	Bottom half center of MFD #3	34	35 D	15 L
Legacy	Center of MK-108	37.5	35 D	55 L
	Center of ADI	28.25	25 D	0

Notes:
(1) R-right, L-left, D-down.

was directly in front of the pilot and required no azimuth adjustment. As shown in Table 4 the measurements to the ADI were more favorable in all aspects (distance, inclination, and azimuth) than the MK-108 or the TOW:TSI page. For these reasons the ADI's location was better suited than the MK-108 or TOW:TSI. While the location of the ADI was more favorable there were downsides to this arrangement. The ADI did not provide a digital readout of track deviation, was located too far away from the MK-108 and, most importantly, did not provide an indication of figure of merit. Both the MK-108 and TOW:TSI provided digital readouts of track deviation. The ADI did have a scale associated with it, however, and while an exact readout of track deviation was not available the fidelity of the scale was such that the pilot could fly the track within prescribed tolerances. With regards to grouping, the ADI and MK-108 were intended to be used together in the legacy cockpit. The location of the ADI relative to the MK-108 was outside the MIL-STD-1472 recommended 30^{o} cone angle and was, therefore, deemed less than desirable. The lack of a FOM for the ADI was deemed a major deficiency, because this information is essential for effective navigation through the minefield. The TOW:TSI provided an indication of figure of merit via the green/yellow/red scheme. As the FOM degraded, the color of the track deviation bar changed. While the ADI's location was more favorable than the TOW:TSI's, the fact that no FOM information was available and the ADI/MK-108 were not sufficiently grouped together lead to the assessment that the legacy cockpit was less suitable than the glass cockpit for display of track deviation.

3.2.3 Coupler Holds

The MH-53E Automatic Flight Control System (AFCS) provided five coupler/hold features relevant to executing an AMCM mission. They were skew hold, tension hold, groundspeed hold, heading hold, and radar altimeter (RADALT) hold. Engagement of any one of the five coupler holds was the same for both the legacy and glass cockpit and was done via the appropriate pushbutton located on the AFCS or Tow control panels (Figure 20). RADALT hold was located on the AFCS control panel and skew, tension, groundspeed, and heading holds were located on the Tow control panel. The AFCS and Tow control panels were located in the center console between the pilot and copilot. The difference between the two cockpits was in the way in which the coupled feature was displayed. In both the legacy and glass cockpit the pushbutton illuminated the desired hold when selected. In addition to the pushbutton illumination, however, the glass cockpit displayed the selected hold on the middle-left side of the TOW:TSI page (Figure 21). The glass cockpit configuration had a clear advantage over the legacy cockpit in that the selected holds display were better grouped with other AMCM displays (i.e., tension, track deviation, skew, etc.) and were located within the optimum viewing angle. This is advantageous in the event a coupled mode is disengaged either intentionally or unintentionally because the pilot will immediately see a change in the selected holds display. In the legacy cockpit the pilot may not immediately recognize the change due to the fact that the AFCS and Tow control panels are not in the

AFCS Control Panel

Tow Control Panel

Figure 20. AFCS and Tow Control Panels.

Source: LCDR Jeff Farlin, Helicopter Mine Countermeasures Squadron FOURTEEN, Norfolk, VA, 2008.

Figure 21. Selected Holds Display.

Source: Rockwell Collins, *United States Navy (USN) CH-53E/MH-53E Communication, Navigation, and Surveillance / Air Traffic Management (CNS/ATM) Upgrade Program Flight2™ Human Machine Interface Design Document (HMIDD), Draft D*, Rockwell Collins, Cedar Rapids, IA, 2007.

primary field of view. The state of the coupler/hold system is a safety of flight issue particularly concerning RADALT hold. Every AMCM mission is conducted with RADALT hold engaged and should this be disengaged for any reason the pilot must know this as soon as possible. An undetected slow descent or slow climb could result in the aircraft impacting the water (especially at the low altitudes where AMCM operations are conducted) or the aircraft pulling the AMCM equipment out of the water.

3.2.4 Mine Field Data

Mine field data consists of distance and time-to-go to the end of the track, track number, track length and field heading (or track course). The glass cockpit displayed the mine field data on the TOW:TSI page in the upper left and upper right corners. As has been previously demonstrated, information displayed on the MK-108 fell well outside the 30^{o} optimum viewing angle and resulted in more "heads down" time in the legacy cockpit. Mine field data in the glass cockpit was grouped with other AMCM critical displays and was more readily viewable to the pilot. Specific measurements to the mine field data from the ADI and the TSI AC symbol are shown in Table 5. Having mine field information co-located with other AMCM displays and not having to constantly look down in the cockpit allows the pilot to better execute the AMCM mission and was considered a more efficient design.

3.2.5 Tension Display

Paragraph 3.1.1 discussed the effects on saliency due to the physical characteristics of the tension display; however, it was also important to note the location of the tension display and its effect on stimulus-response compatibility (SRC). SRC suggests that the *"response is quicker when there is a spatial congruence between the stimulus and required action item"*.[13] The SRC for the tension display in the glass cockpit met the desired compatibility requirement because it was on the right side of the display and the right hand controls the cyclic, which in turn controls cable tension. For example, when the cyclic is pushed forward groundspeed increases and the increase in tension is viewed by the display bar filling in an upward direction. The converse is the case when the cyclic is moved aft. The location of the tension display in the legacy cockpit was considered less compatible with regards to stimulus-response due to the fact that it was located to the left of the pilot.

3.3 Labeling of AMCM Displays

Correct labeling of displays provides the pilot the information needed to minimize mental workload. To effectively conduct the AMCM mission the display of information should be instantly recognizable. A display that is unambiguous clearly presents information in such a way that the operator easily comprehends what is being presented. As Hawkins states, "*Ambiguity increases cognitive workload on the crew member as well as inducing errors."*[11] The objectives with regards to AMCM display labeling was to evaluate whether or not the glass and

legacy displays were correctly labeled and the information presented on them was unmistakable.

3.3.1 Skew Display Scale

The skew display scale for both the glass and legacy cockpits were identical except for the labeling used to indicate skew angle. Skew angle is the angle between the tow cable and the center-line of the aircraft. For example, a skew angle of 0^{o} would indicate that the tow cable is directly behind the aircraft at the 6 o'clock position. Skew angle is important to monitor for two reasons. First, when flying along a track if the skew angle is not zero, while the aircraft may be on track, the towed device may not be on track. Secondly, because the tow boom is located inside the aircraft the left-to-right movement of the boom is limited to the width of the cabin. If the skew angle is too great (> approximately 12^{o}), the tow boom may impact the cabin wall. The skew scale in the glass cockpit had labels on all of the major graduation marks, whereas the skew scale in the legacy cockpit did not. The difference was that the legacy cockpit did not have a label under the major graduation mark for skew angles of 5^{o} left or right, but the glass cockpit did. While the pilot could infer that the un-labeled graduation mark was 5^{o} by counting the number of minor graduation marks, this resulted in an increase in mental workload that could have been avoided by simply labeling the major graduation mark. Additionally, MIL-STD-1472 states *"Except for measurements that are normally expressed in decimals, whole numbers shall be used for major graduation marks."*[8] The legacy skew display

did not meet this requirement, while the glass skew display did. The labeling of the skew scale in the glass cockpit better conveyed the skew angle than did the legacy skew scale and was considered a better choice for conducting the AMCM mission.

3.3.2 Distance-To-Go (DTG)

As discussed in paragraph 3.2.4 DTG was displayed on the MK-108 in the legacy cockpit and the TOW:TSI page in the glass cockpit. In the legacy cockpit there were no units associated with the display of DTG. In the glass cockpit, DTG was clearly labeled with "YDS" when the DTG was less than 10 NM and with "NM" when the DTG was greater than 10 NM. Of all the mine field information presented to the pilot, DTG was considered one of the most important. It was critical for the pilot to know how much time he had until the end of the track so he could prepare for the turn to the next track. The inclusion of units on DTG in the glass cockpit left no doubt as to what type of information was being provided and was considered a more efficient design than the unit-less DTG displayed in the legacy cockpit.

3.4 Physical Workload

Certain AMCM tasks were evaluated quantitatively in order to measure the amount of physical workload required in both the legacy and glass cockpits when conducting the AMCM mission. Specifically, the AMCM tasks that were analyzed were the number of button presses required to select a track and the physical

effort required to reach those buttons. Physical effort was evaluated by defining where the track selection buttons were located within the three functional reach zones described in Section 2.5.

3.4.1 Track Selection Button Pushes

Selection of the desired track was performed by manually entering the track, or by selecting a programmed track from a list. Selection of the next track (whether manual or programmed) was done via the MK-108 in the legacy cockpit and the CDU-7000 in the glass cockpit. Table 5 is a side-by-side comparison of the legacy cockpit and the glass cockpit with the steps and number of button pushes required to enter a programmed track. The side-by-side comparison is not intended to show any equivalency between the legacy and glass cockpits with regards to the actions of each step, but rather to show the number of steps required to enter a programmed track.

For the legacy cockpit, five steps were required to select a programmed track. The first step was to press the track (TRK) button on the MK-108 (see Figure 9). This put the MK-108 in a stand-by mode in preparation for track selection. Stand-by mode was indicated by a white “L” located at the bottom center of the display. The second step was to press the enter (ENT) button. This action took the MK-108 out of track selection stand-by mode, indicated by the white “L” extinguishing, and subsequently displayed the track selection menu. The track selection menu consisted of up to 11 tracks per page. Cycling through the pages was accomplished via the page up (PGU) and page down (PGD) keys.

Table 5: Selection of a Programmed Track

Step	Legacy (MK-108)	# of Button Pushes	Glass Cockpit (CDU-7000)	# of Button Pushes
1	Press the Track (TRK) button. A white highlighted "L" appears in the acknowledge indicator position indicating that the track select function is in standby. The track selection menu is NOT displayed, yet.	1	Press the Mission (MSN) button to bring up the Mission page.	1
2	Press the Enter (ENT) button. The "L" extinguishes and the track selection menu is now displayed.	1	From the Mission page press the TOW LSK to bring up the Tow Control page.	1
3	Press Page Up (PGU) and Page Down (PGD) buttons as required until the page with desired track is displayed. There can be a maximum of 22 pages to scroll through depending on the number of assigned tracks.	21 max 0 min	From the Tow Control Page press the TRACKS LSK to bring up the Tracks page.	1
4	Press the up and down arrows as required to highlight the desired track. There can be up to 12 tracks per page.	11 max 0 min	Press the up arrow and down arrow keys as required until the page with desired track is displayed (maximum of 24 pages,11 tracks per page available depending on number of assigned tracks).	23 max 0 min
5	Press the Enter (ENT) button to select the desired track.	1	Press the LSK adjacent to the desired track to highlight the track with an asterisk indicating that track selection is in standby.	1
6			Press the same LSK to confirm and select the desired track.	1
	TOTAL-->	35 max 3 min	TOTAL-->	28 max 5 min

There can be a maximum of 22 pages to scroll through. Step three was to page up or page down as required until the page with the desired track was displayed. Step four was to select one of the eleven displayed tracks by pressing the up or down arrow keys until the desired track was highlighted. The final action, step 5, was to press the ENT button thereby telling the system that the highlighted track is the desired track which then provided the appropriate navigation information to the pilot.

For the glass cockpit, six steps were required to select a programmed track. The first step was to press the mission (MSN) key on the CDU-7000 (see Figure 13). This action would bring up the mission page. The mission page had selections for various mission sub-systems, one of them being the tow mission. Step two was to select the line select key (LSK) adjacent to “TOW”. This action would bring up the Tow Control Page. From the Tow Control Page, the operator could set various AMCM related parameters one of which was track selection. Step three was to select the “TRACKS” LSK which subsequently would display the Tracks page. On the Tracks page, up to 11 tracks per page may be displayed. Cycling through the Tracks pages was accomplished via the up and down arrow keys. There could be up to 24 pages to scroll through. Step four was to arrow up or arrow down as required until the Tracks page with the desired track is displayed. Step five was to select the LSK adjacent to the desired track. After the first push of the desired tracks LSK, an asterisk is displayed next to the desired track indicating that the selection of that particular track is in stand-by. A

second push of the same LSK, step six, is required to confirm the track selection. After step six the desired track has been loaded into the system and navigation information to the selected track is being provided to the pilot.

As shown in Table 5, the maximum number of button pushes possible for the MK-108 was 35 and for the CDU-7000 was 28—an advantage for the CDU-7000. The minimum number of button pushes possible was three for the MK-108 and five for the CDU-7000—an advantage for the MK-108. In order to determine which interface had the least workload with regard to button pushes, a comparison of minimum and maximum button pushes was conducted. With respect to using the MK-108 for track selection, there were only two scenarios where the minimum number of button pushes was less than that required for the CDU-7000, and seven scenarios where the maximum number of button pushes was greater than that required for the CDU-7000. The number of button pushes (max, min or somewhere in between) was entirely dependant on the number of assigned tracks for a given mission. The more tracks assigned, the more pages of tracks the operator would be required to cycle through to find the desired track. In the author's experience, however, tracks assigned during a single AMCM mission rarely exceed 20. With 20 assigned tracks the desired track would either be on the first page (0 push) or second page (1 push) of tracks on either the MK-108 or CDU-7000. The CDU-7000 has an advantage in Step 5 where the desired track can be selected directly by pressing the line select key adjacent to the desired track. With the MK-108, the operator is required to scroll through the

tracks one-at-a-time (up to 11 button pushes) until the desired track is highlighted before that track can be selected. For this reason, the workload required to select a programmed track via the MK-108 was considered greater than that of the CDU-7000. It should also be noted that while the number of steps required to select a programmed track is greater for the CDU-7000 verse the MK-108 (six steps verse five steps), for most cases the number of button pushes was less.

For the manual selection of a track, the number of button pushes was noticeably lower than what was required for selecting a programmed track. Table 6 illustrates the steps required to enter a track manually. For the MK-108 maximum number of button pushes was eight and the minimum was three. For the CDU-7000 maximum button push was nine and the minimum was five. For both maximum and minimum button pushes the CDU-7000 was higher than the MK-108 and, therefore, resulted in a higher workload.

3.4.2 Track Selection Functional Reach Zones

In addition to the number of button pushes required to select a track, the physical effort required to reach the appropriate buttons on the CDU-7000 and MK-108 was also evaluated. Both the CDU-7000 and MK-108 controls were characterized by their Functional Reach Zones for both a male 93rd percentile and a female 5th percentile as measured from the right seat. As mentioned in Section 2 the location of the seat in the legacy cockpit was adjusted to match that of the CNS/ATM prototype lab since the seat in the prototype lab was fixed.

Table 6: Manually Selecting a Track

Step	Legacy (MK-108)	# of Button Pushes	Glass Cockpit (CDU-7000)	# of Button Pushes
1	Press the Track (TRK) button. A white highlighted "L" appears in the acknowledge indicator position indicating that the track select function is in standby. The track selection menu is NOT displayed, yet.	1	Press Mission (MSN) button to bring up the Mission page.	1
2	Enter desired track # via the numeric keypad. The track # can be anywhere from 0 to 20000. A "-" sign is required at the beginning of the track # to enter a track located on the left side of the minefield. The "-" sign is not required for tracks located on the right side of the minefield.	6 max 1 min	From the Mission page press the TOW LSK to bring up the Tow Control page.	1
3	Press the Enter (ENT) button to select the desired track.	1	Enter desired track # via the numeric keypad. The track # can be anywhere from 0 to 20000. The letter "L" is required at the beginning of the track # to enter a track located on the left side of the minefield. The letter "R" is required for tracks located on the right side of the minefield.	6 max 2 min
4			Press the NEW TRACK LSK to select the desired track.	1
	TOTAL-->	8 max 3 min	TOTAL-->	9 max 5 min

In the following figures Reach Zone 1 is highlighted in green, Reach Zone 2 in yellow, and Reach Zone 3 in red. As mentioned in section 2, the functional fingertip reach of the male evaluator was in the 93rd percentile and the female evaluators were in the 5th percentile.

For the 93rd percentile evaluator sitting in the right seat of the glass cockpit, all of the buttons pushes required to enter a track manually, with the exception of the MSN key, were located within the green zone. The MSN key was located in the yellow zone. To enter a programmed track, the reach zones were either green or yellow depending on which LSK was associated with the desired track. If the desired track was located on the left side of the display then the Reach Zone was yellow. If it was located on the right side of the display the Reach Zone was green. These relationships for the 93 percentile evaluator are shown in Figures 22 and 23. For the 5th percentile female evaluator all of the buttons required to enter a programmed track or manual track were located within yellow or red zones. There were no buttons located within the green zone. The MSN key, numeric keypad, and left LSK's were all located within the red zone. All other buttons required to select a track were located within the yellow zone. The 5th percentile female aviator will have to unlock her harness in order to enter a manual track since almost all (the number "9" button being the only exception) of the numeric key pad and the NEW TRACK LSK are within the red zone. To select a programmed track, the 5th percentile pilot will also have to

Figure 22. CDU-7000 Tow Control Pg With Male 95th Percentile Reach Zones

Source: Rockwell Collins, *United States Navy (USN) CH-53E/MH-53E Communication, Navigation, and Surveillance / Air Traffic Management (CNS/ATM) Upgrade Program Flight2TM Human Machine Interface Design Document (HMIDD), Draft D*, Rockwell Collins, Cedar Rapids, IA, 2007.

Figure 23. CDU-7000 Tow Tracks Pg With Male 95th Percentile Reach Zones

Source: Ibid

unlock her harness since the TRACKS LSK in within the red zone. On the Tracks page the bottom four right LSK's were within the yellow zone and all other LSK's were in the red zone. These relationships for the 5th percentile evaluator are depicted in Figures 24 and 25.

For the 93rd percentile evaluator evaluating the MK-108 from the right seat all of the buttons required to enter a programmed track or manual track was located within the yellow zone, with the exception of the track (TRK) button. The TRK button was located in the red zone, requiring the evaluator to release his harness in order to actuate the button. There were no buttons within the green zone. Most buttons were located within the yellow zone with the exception of the two columns of buttons located on the far left of the display unit as shown in Figure 26. For the 5th percentile female evaluator sitting in the right seat there were no buttons within the green zone, only one button within the yellow zone and the rest of the buttons were in the red zone (see Figure 27). The only button located within the yellow zone was the number "9" numeric key. This meant that the 5th percentile female evaluator could not reach the MK-108 to select a programmed track or manual track without first releasing her seatbelt harness.

When comparing the Functional Reach Zones for the CDU-7000 and MK-108 it was evident that the CDU-7000 was more "reachable" than the MK-108 for the 93rd percentile evaluator. For the 5th percentile evaluator, however, most of the keys required to enter a track in the CDU-7000 were in the red zone and all of the keys required to enter a track in the MK-108 were in the red zone. In

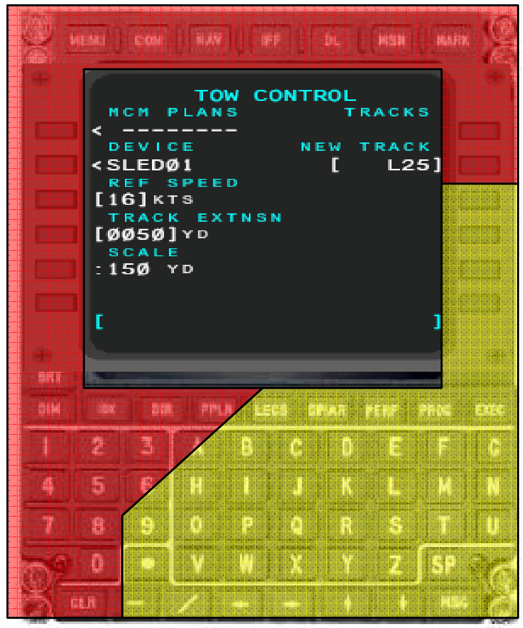

Figure 24. CDU-7000 Tow Control Pg With Female 5th Percentile Reach Zones

Source: Ibid.

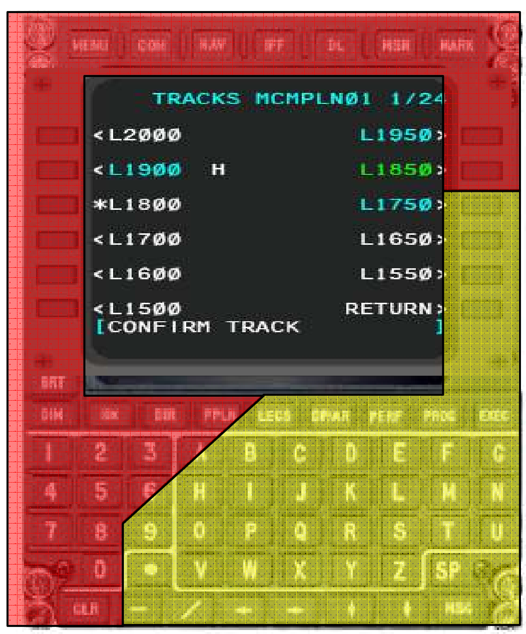

Figure 25. CDU-7000 Tow Tracks Pg With Female 5th Percentile Reach Zones

Source: Ibid.

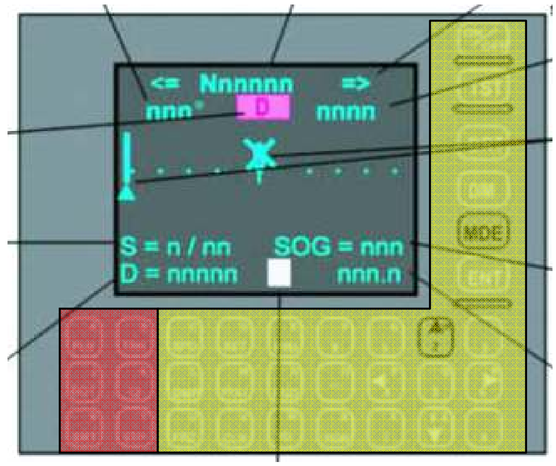

Figure 26. MK-108 With Male 95th Percentile Reach Zones

Source: Naval Air Systems Command, *Draft MH-53E Naval Aviation Technical Information Product (NATIP), NTRP 3-22.4-MH53E,* Airworthiness Office (AIR-4.0P) NATIP Division, Patuxent River, MD, 2006

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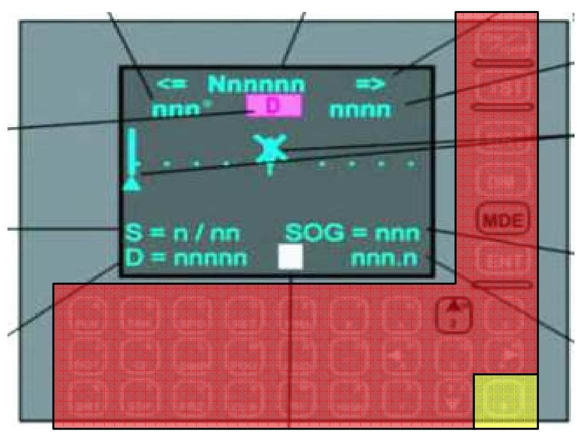


Figure 27. MK-108 With Female 5th Percentile Reach Zones

Source: Ibid

either case, the 5th percentile evaluator will be required to unlock her harness in order to select a programmed or manual track. The main factor affecting the accessibility of the two control panels was the physical location of the CDU-7000 as compared to the MK-108. The MK-108 was located in the top-center of the center console while the CDU-7000 was located on the top-right of the center console. While the 5th percentile evaluator had to unlock her harness for either the MK-108 or CDU-7000, the CDU-7000 had a slight advantage in that it was physically closer to the evaluator than the MK-108 by approximately three inches. The physical effort required to select a track was less when utilizing the CDU-7000 and was considered a better design for executing the AMCM mission.

3.5 Mental Workload

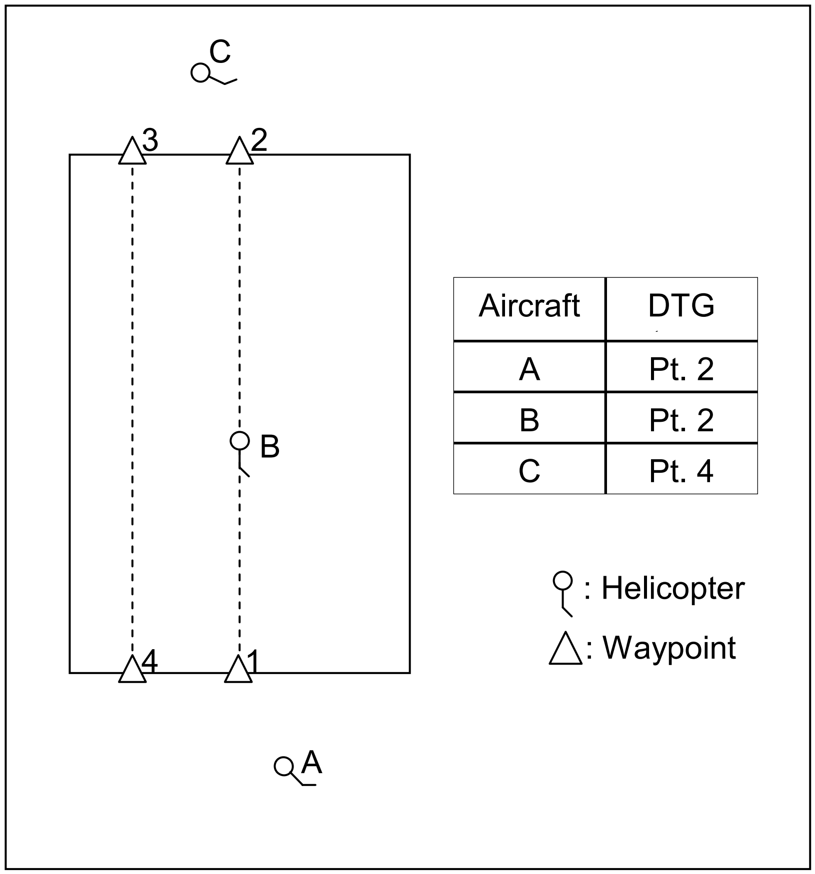
With regards to mental workload, a limited, qualitative analysis was conducted. MIL-STD-1472 states *"Information shall be presented to the operator in a directly usable form. Requirements for transposing, computing, interpolating, or mentally translating into other units shall be avoided."*[8] A qualitative evaluation of the functionality of the MK-108 revealed that the distance-to-go function would contribute to an increase in mental workload over the glass cockpit. This was due to the fact that DTG information displayed by the MK-108 was not always presented in a "directly usable form" while the DTG information displayed by the TOW:TSI page was. As will be discussed, the format that legacy DTG data was presented required the operator to perform mental calculations in real-time in order to determine the aircraft's position relative to the minefield. Such mental

calculations were not required in the glass cockpit as the DTG information was presented in a directly useable form.

3.5.1 Distance-To-Go

DTG information was located on the MK-108 and TOW:TSI page for the legacy and glass cockpits respectively. DTG on the MK-108 was always the distance from the aircraft to the far end of the field or the end of the track. This functionality worked fine when the aircraft was inside the mine field, but was less intuitive when the aircraft was outside of the minefield. When maneuvering the aircraft to intercept the desired track from outside of the minefield, knowing the distance to the beginning of the minefield, or track, was more important than knowing the distance to the end of the track. This was important to ensure the aircraft was stable and on track prior to entering the minefield. In order for the pilot to determine the distance to the beginning of the field, the known length of the track had to be subtracted from the displayed DTG. For example, if the DTG was 3250 yds and the track length was 2175 yds the distance to the beginning of the track was 1075 yds. DTG in the glass cockpit by comparison did not require any mental calculations to the first waypoint on the track. In the glass cockpit DTG was the distance to the next waypoint in the AMCM plan. Therefore, when maneuvering outside of the minefield, the DTG was to the first waypoint at the beginning of the track and when in the minefield, it was the distance to the waypoint at the end of the track. As the aircraft exited the minefield and captured the end waypoint, navigation guidance was updated to provide DTG to the next

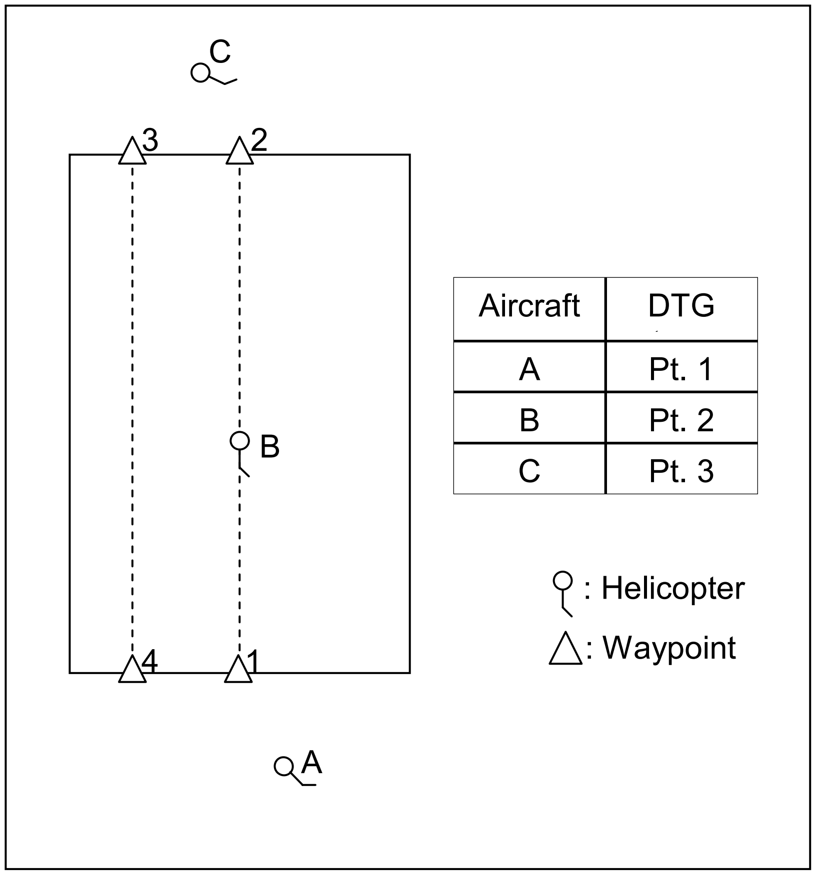
waypoint which was located at the beginning of the next track. Thus, DTG to the beginning or end of the track (depending on if the aircraft was outside or inside the minefield) was always provided to pilot in a more “useable form” than that provided by the MK-108. Figure’s 28 and 29 provide a graphical illustration of how the legacy and glass cockpits determined DTG.



Aircraft	DTG
A	Pt. 2
B	Pt. 2
C	Pt. 4

Figure 28. MK-108 DTG Logic.

Source: Created by the author using Microsoft Office PowerPoint 2003, 2008.



Aircraft	DTG
A	Pt. 1
B	Pt. 2
C	Pt. 3

Figure 29. CNS/ATM DTG Logic.

Source: Ibid.

SECTION IV: CONCLUSIONS AND RECOMMENDATIONS

The ultimate purpose of this thesis was to determine which cockpit configuration (legacy or glass) was best suited, from a human factors perspective, to conduct the AMCM mission. To determine this, a detailed examination of differences in AMCM displays as installed on the MH-53E legacy and glass cockpits was conducted. Specifically, AMCM display characteristics, location, grouping, and labeling were compared and contrasted between the two cockpits. In all categories, the glass cockpit was the better choice. This was due to 1) increased saliency due to color displays, 2) better grouping due to AMCM displays located within the optimum viewing angle, and 3) better labeling due to clearly defined scales and units of measure. The AMCM displays in the legacy cockpit were 1) less salient due to monochromatic displays and lack of skew trending information, 2) poorly grouped due to the remote location of the MK-108, and 3) poorly labeled due to lack of scale definition and units of measure.

In addition to the research conducted on the AMCM displays, a limited assessment of the mental and physical workload aspects of executing the AMCM mission was also conducted. Specifically, the physical workload associated with selecting a programmed or manual track as well as the mental workload associated with determining distance-to-go was evaluated. With regards to track selection both cockpits were fairly similar when measuring the number of key presses required to select a track. The glass cockpit was better when selecting a programmed track, while the legacy cockpit was better when selecting a track

manually. It was also determined that based on functional reach, the effort required to press buttons on the MK-108 was greater than that of the CDU-7000. Mental workload was qualitatively evaluated and the glass cockpit was determined to be the better choice. This was due to the clearly displayed DTG information whether flying to the beginning or end of a track as opposed to the mental calculations required in the legacy cockpit to determine the DTG when flying to the beginning of a track.

There is no doubt that either the legacy cockpit or the glass cockpit configuration can successfully carry out the AMCM mission. Even a cockpit laden with many human factors deficiencies, as is the case with the legacy cockpit, can be overcome due to the adaptable nature of man. This does not, however, imply that human factors engineers or aircrew should settle for a cockpit design that is something less than desirable. Hawkins stated it best when he said:

> *"Man is adaptable as an operator and this adaptability often masks display and control deficiencies which nevertheless remain to trap the unfortunate or unwary."*[11]

In the legacy cockpit the pilot was required to be more "adaptable" than what was required for the glass cockpit. From a human factors perspective, the glass cockpit was the better choice for conducting the AMCM mission efficiently and safely.

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APPENDIX

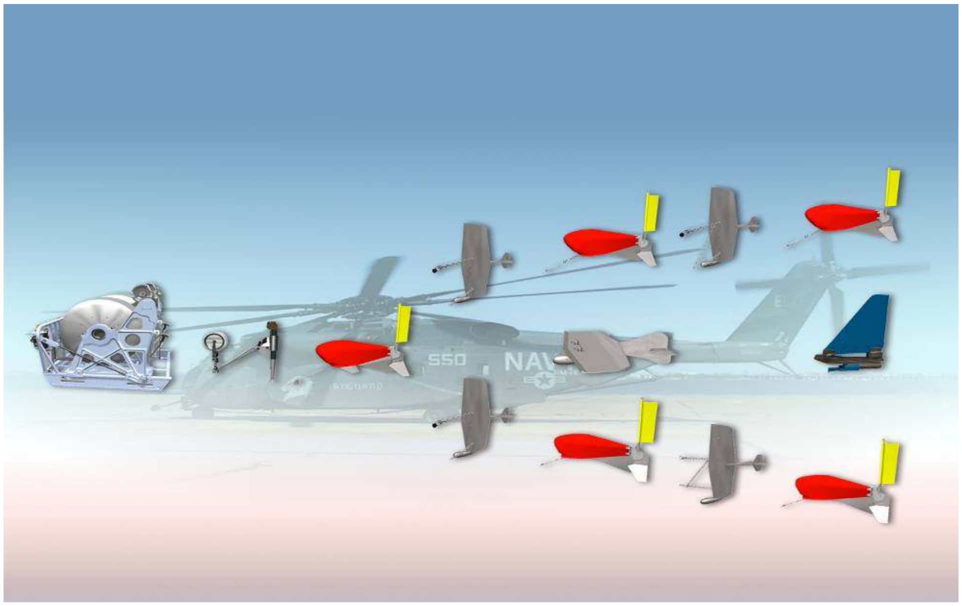

Figure A-30. MK-103 Mechanical Minesweeping Equipment.

Source: AZ1 (AW) Sherri Jenkins, Helicopter Mine Countermeasures Squadron FOURTEEN, Norfolk, VA, 2008.

Figure A-31. MK-104 Acoustic Influence System.

Source: Ibid.

Figure A-32. MK-105 Magnetic Influence System.

Source: Ibid.

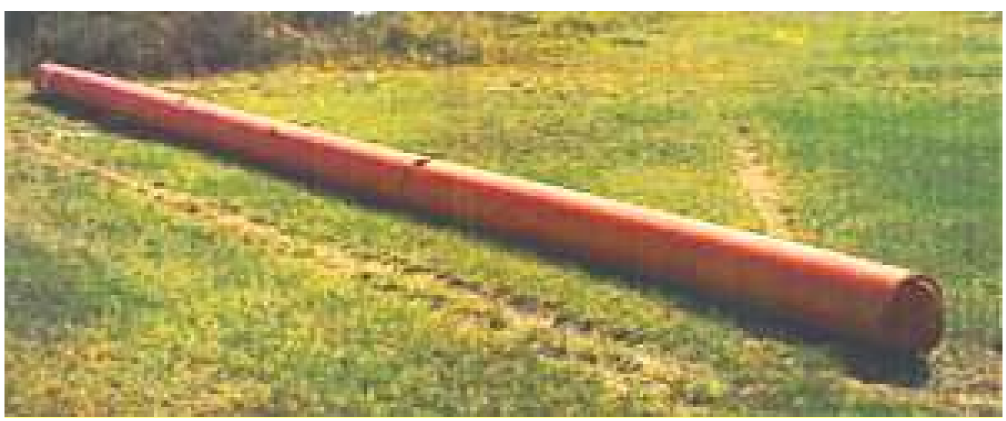

Figure A-33. AN/SPU-1W Magnetic Influence System.

Source: Ibid.

Figure A-34. AN/AQS-24 Minehunting Equipment.

Source: Ibid.

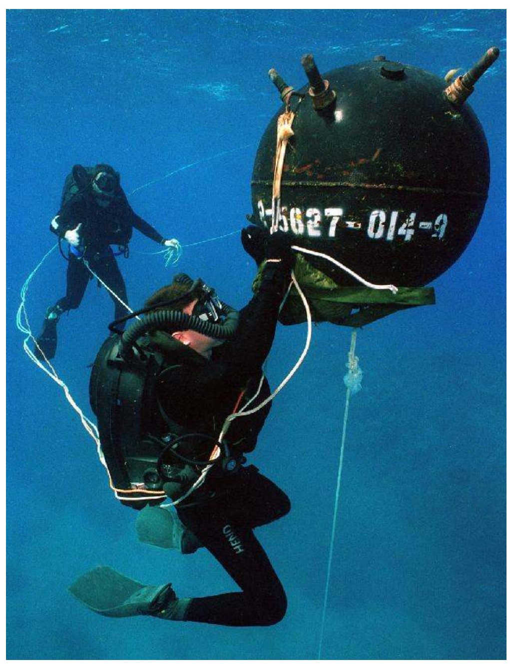

Figure A-35. Diver Attaching an Inert Charge to a Moored Mine.

Source: URL: http://www.specialoperations.com/Images_Folder/POM/eod-mine.jpg [cited 2/28/08].

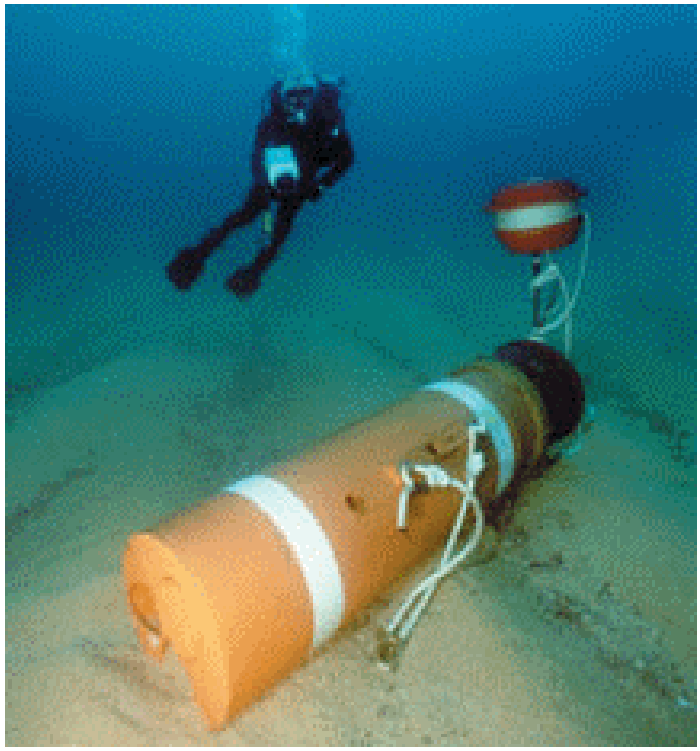

Figure A-36. Diver Viewing an Exercise Bottom Mine.

Source: URL: http://www.navy.mil/navydata/policy/vision/vis02/p125-a.gif [cited 2/28/08].

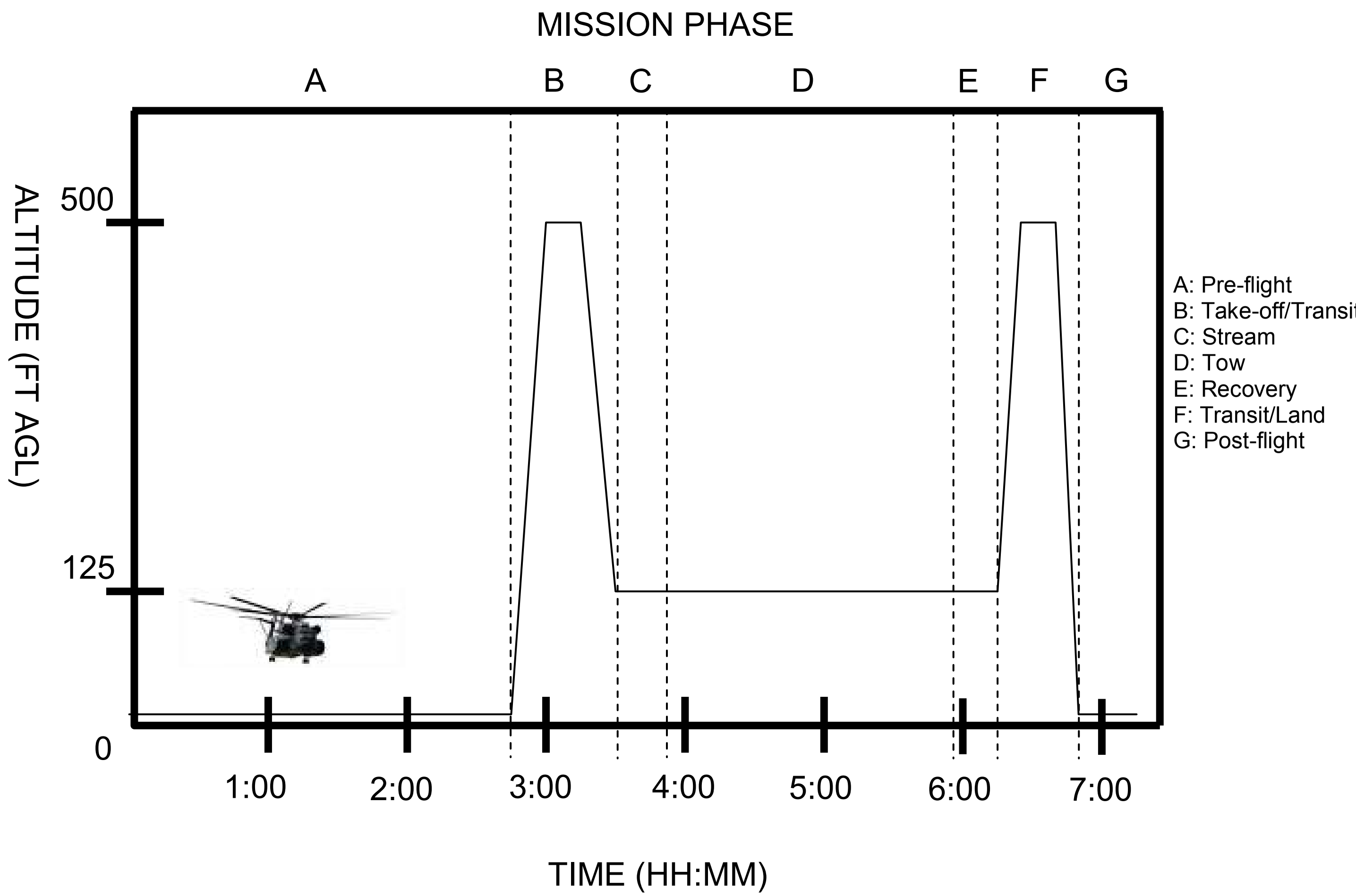

Figure A-37. AMCM Mission Timeline.

Source: Created by the author using Microsoft Office PowerPoint 2003, 2008. Clip art from URL: http://www.fotosearch.com/thumb/OMU/OMU151/MH-53ESeaDragonFlying.jpg [cited 2/29/08].

Table A-7: Test and Test Procedures.

Test Objective [1]	Evaluate	Remarks [2]
Physical Characteristics and Grouping		
Tension Display	Evaluate physical characteristics, location and grouping with other AMCM instruments in both the legacy and glass cockpits.	Measure eye distance and head azimuth to the tension display. Measure distance from display to all other AMCM displays. Determine if display falls with the optimum 30^o cone angle. Qualitatively evaluate salience of the display noting location, color, and shape.
Skew Display	Evaluate physical characteristics, labeling, and grouping with other AMCM instruments in both the legacy and glass cockpits.	Measure eye distance and head azimuth to the skew display. Measure distance from display to all other AMCM displays. Determine if display falls with the optimum 30^o cone angle. Qualitatively evaluate salience of the display noting location, color, and shape. Evaluate labeling with regards to the arrangement of scale graduation marks.
Track Deviation	Evaluate physical characteristics, location, and grouping with other AMCM instruments in both the legacy and glass cockpits.	Measure eye distance and head azimuth to the track deviation indication. Measure distance from display to all other AMCM displays. Determine is display falls with the optimum 30^o cone angle. Qualitatively evaluate salience of the display noting location, labeling, and color.
Coupler Holds	Evaluate indications of an engaged coupled mode in both the legacy and glass cockpits. Evaluate location and grouping with other AMCM instruments in both the legacy and glass cockpits.	Note how a positive engagement of RADALT hold, skew hold, tension hold, groundspeed hold, and heading hold are indicated. Measure distance from display to all other AMCM displays.

Test Objective [1]	Evaluate	Remarks [2]
Minefield Data	Evaluate physical characteristics and grouping with other AMCM instruments in both the legacy and glass cockpits.	Measure eye distance and head azimuth to the minefield data fields. Measure distance from display to all other AMCM displays. Determine if display falls with the optimum 30^{o} cone angle. Qualitatively evaluate salience of the display noting location, labeling, and color.
Distance-To-Go (DTG)	Evaluate DTG labeling for both the legacy and glass cockpits.	Evaluate labeling with regards to how the units of measure are displayed.
Physical Workload		
Track Selection	Evaluate physical workload required to select a track in both the legacy and glass cockpits.	Count the number of button pushes required to select a programmed track or a manual track using the CDU-7000 or MK-108.
Track Selection Accessibility	Evaluate accessibility of the controls required to select a track in both the legacy and glass cockpits using a 5th and 93rd shoulder-to-fingertip reach percentile.	Determine which of the three functional reach zones were required for reaching the track select controls. Attempt to actuate track selection controls with the harness locked and unlocked.
Mental Workload		
Distance-To-Go (DTG) Calculation	Evaluate mental workload required to understand DTG information in both the legacy and glass cockpits.	Qualitatively determine if DTG information is presented in such a way that mental calculations are not required.

Notes:
(1) Evaluation of the glass cockpit was conducted at the prototype lab located in Patuxent River, MD which was considered representative of the actual aircraft. At the time of the evaluation there was no CNS/ATM equipped aircraft. The evaluation of the legacy cockpit was conducted in the MH-53E simulator and an MH-53E helicopter, both located in Norfolk, VA.
(2) Evaluation was conducted with personnel in full summer flight gear with harness both locked and unlocked for switch actuation assessment. Distance measurements were taking using a tape ruler with 0.0625 inch accuracy. Azimuth measurements were taken using a protractor with 1^{o} accuracy.

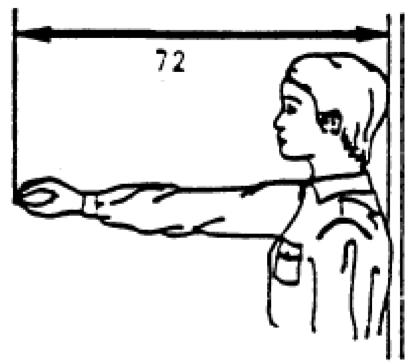

Figure A-38. Functional Reach.

Source: Department of Defense Handbook, *Anthropometry of U.S. Military Personnel, DOD-HDBK-743A,* U.S. Army Natick Research, Development and Engineering Center, Natick, MA, 1991.

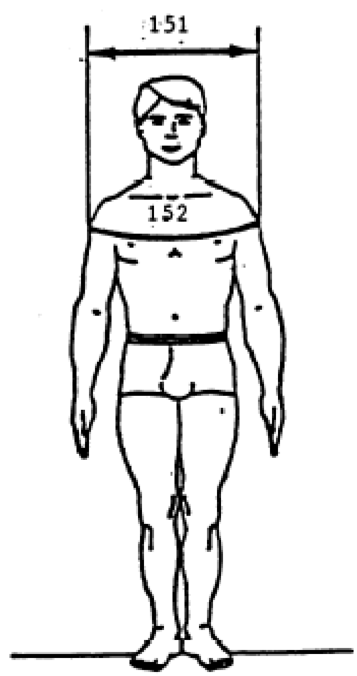

Figure A-39. Bideltoid Breadth.

Source: Ibid.

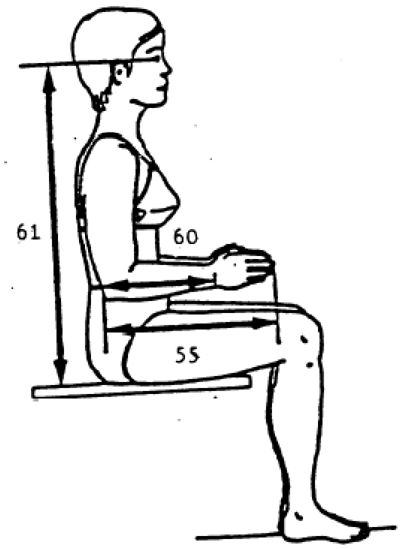

Figure A-40. Sitting Eye Height.

Source: Ibid.

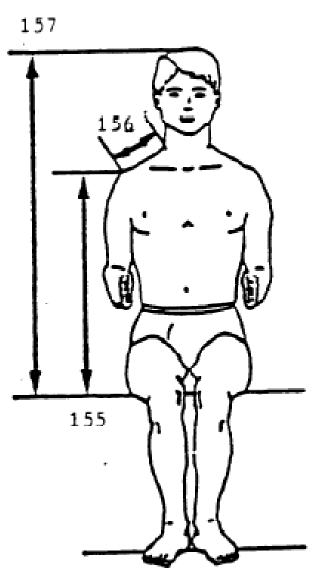

Figure A-41. Sitting and Acromiale Height.

Source: Ibid.

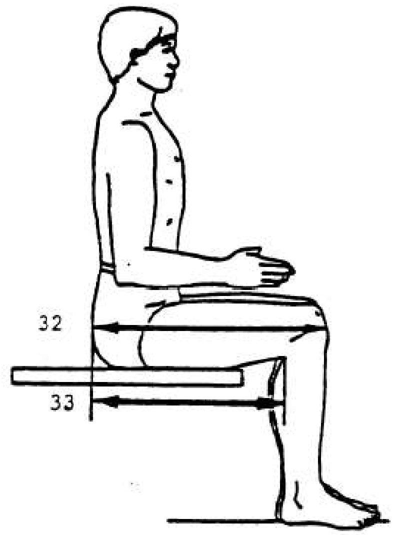

Figure A-42. Buttock-to-Knee Length.

Source: Ibid

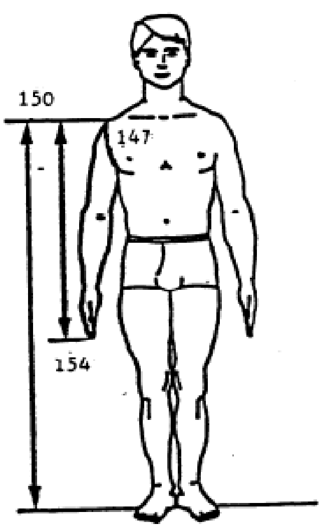

Figure A-43. Shoulder-to-Fingertip Length.

Source: Ibid.

Table A-8: Evaluator's Flight Equipment

Item	Federal Stock Number
Helmet, Protective	8475-01-387-6711
Gloves, Flyers Summer	8415-01-029-0111
Coveralls, Flyers Summer	8415-01-351-0330
Boots, Flyers – Steel Toe	8430-00-624-2797
Vest, Survival	8415-01-442-1991
Clipboard Pilots, Black	8475-00-433-2073
Life Preserver	1680-01-483-4390

Figure A-44. Standing Evaluator Equipped with Summer Flight Gear.

Source: LCDR Josh Kinnear, Helicopter Mine Countermeasures Squadron FOURTEEN, Norfolk, VA, 2008

Figure A-45. Sitting Evaluator Equipped with Summer Flight Gear.

Source: LCDR Josh Kinnear, Helicopter Mine Countermeasures Squadron FOURTEEN, Norfolk, VA, 2008

VITA

Lieutenant Commander (LCDR) Jeff Farlin, United States Navy, was born in Big Rapids, MI on August 13th, 1970. He was raised in the Detroit, MI area and graduated from Ferndale High School in 1988. After graduation he enlisted in the Navy as an Aviation Anti-Submarine Warfare Operator (AW). LCDR Farlin attended the P-3 Fleet Replacement Squadron (FRS) VP-30 in Jacksonville, FL before transferring to VP-49, also in Jacksonville, in 1989 for his first operational tour where he served as the Tactics Petty Officer and logged over 500 hours of special crew time. In 1991, LCDR Farlin applied and was accepted to the United States Naval Academy. He entered the Naval Academy in 1992 and was commissioned as an Ensign with the Class of 1996 with a Bachelor of Science degree in Astronautical Engineering. Following graduation from the Academy, LCDR Farlin attended pilot flight training in Pensacola, FL. In August 1998, LCDR Farlin was designated an unrestricted aviator and was stationed with Airborne Mine Countermeasures Squadron Fifteen (HM-15) in Corpus Christi, TX as an MH-53E pilot. With HM-15 he served as the Tactics Officer and Mine Warfare Officer. LCDR Farlin logged approximately 800 hrs with HM-15 as an aircraft commander, functional check pilot, and instrument instructor. Upon completion of this tour with HM-15, LCDR Farlin applied and was accepted to the United States Naval Test Pilot School (USNTPS) in Patuxent River, MD. LCDR Farlin graduated with USNTPS Class 125 in June 2004 and subsequently transferred to Air Test and Evaluation Squadron Two-One (HX-21) where he

served as the Organic Airborne Mine Countermeasures (OAMCM) Project Officer for the MH-60S test program. In August of 2006, LCDR Farlin left HX-21 and began working at PMA-261, the Navy and Marine Corps H-53 Heavy Lift Helicopter Program Office. While at PMA-261, LCDR Farlin served as the Project Officer for the CNS/ATM Upgrade and the Integrated Mechanical Diagnostics Systems (IMDS) projects. In August of 2007, he transferred to Helicopter Mine Countermeasures Squadron Fourteen (HM-14) where he is currently serving as a Department Head. LCDR Farlin has flown over 30 different type/model/series of rotary wing and fixed wing aircraft and is a member of the Society of Experimental Test Pilots (SETP).