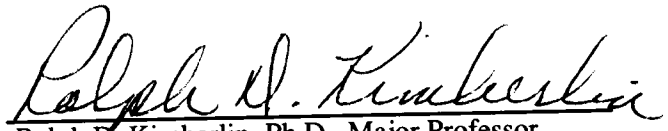
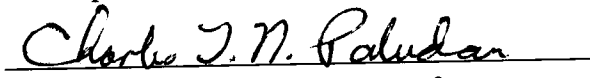


To the Graduate Council:

I am submitting herewith a thesis written by David A. Downey entitled "Analysis of the MH-47E Integrated Avionics System." I have examined the final 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 Management.


Ralph D. Kimberlin, Ph.D., Major Professor

We have read this thesis and recommend
its acceptance:




Accepted for the Council:


Associate Vice Chancellor
and Dean of the Graduate School

**ANALYSIS OF THE MH-47E
INTEGRATED AVIONICS SYSTEM**

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

David A. Downey

August 1995

ABSTRACT

The United States Special Operations Command has a worldwide deployment mission. In support of this mission, the United States Army provides helicopter support with the MH-60K and the MH-47E. Both aircraft are equipped with a glass cockpit architecture called the Integrated Avionics System (IAS). The IAS is not user friendly. It is cumbersome to work with and does not facilitate the mission flexibility required in this hostile flight environment. The special operations flight environment is high workload. The overly complicated and poorly designed IAS installed in the MH-47E was a causal factor in a near accident.

The poor IAS design and implementation is caused by the designer and manufacturer failing to follow established guidelines as outlined in the Military Standards and Specifications. This incident was precipitated by the violations of the intent of the applicable Standards and Specifications. The Multi-Function Displays' design is cluttered and needlessly "busy". It is further concluded that the cockpit integration violates the intent of any aircraft enhancement. Any enhancement to an aircraft system (helicopter and/or pilot) should reduce the pilot workload by either off-loading tasks or automating functions. It is apparent that systems and controls have been automated to integrated within the IAS just because the technology permitted it. The obvious lack of system analysis by the designer is considered a causal factor. The lack of a system engineering breakdown of critical flight tasks, specifically mode switching is a major deficiency. The implications of the system engineering deficiencies include the lack of crew coordination, pilot workload, pilot situational awareness and crew excess capacity versus workload saturation.

Finally, the U.S. Special Operations Command is faulted for expecting this aircraft/pilot system to be capable of performing all the missions envisioned. The MH-47E is too complicated and crews will never fully understand the systems due to the shear volume of information and complexity.

There are two possible recommendations to fix the IAS. The first would be to start all over from the beginning. This approach, although appearing to be possible, is fiscally and politically not possible. The second approach is to fix what can be fixed and continue to improve the IAS and it's

components. The later approach has the best possibility of success. A carefully thought out plan is the most realistic.

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PART 1: INTRODUCTION

The U.S. Army's Airworthiness Qualification Test Directorate was involved in a near accident involving the MH-47E Chinook helicopter in July 1994.¹ The events surrounding this incident are complex and this thesis is inspired by the incident. The crew was two experimental test pilots performing a developmental test flight on the MH-47E's new Integrated Avionics Sub-System, a "glass cockpit" architecture. The incident maneuver was a coupled approach to an automatic hover over Kentucky Lake. The copilot announced and deselected the radar altitude hold capture. The handling pilot did not hear the deselection announcement from the copilot. Post-flight review of the cockpit video and audio verifies the deselection announcement and no reply from the flying pilot. Consequently the aircraft, in a normal decent profile at 500 ft/min, flew through the 50-foot capture altitude. Prompt pilot action and a large power application recovered the aircraft with the aft wheels within 5 feet of the water.

New is not necessarily better. This statement can be applied to the "glass cockpits" of both the MH-47E and the MH-60K (Figure 1). The cockpits are virtually the same in both aircraft. All primary flight, engine, and navigation displays as well as interface with the aircraft are via multi-function cathode ray tube displays. The special operations flight environment involves high levels of workloads. The typical special operations helicopter mission is a three to nine-hour, low-level (200 feet and below) night ingress/egress using night vision goggles. The Integrated Avionics Subsystem (IAS) "glass cockpit" architecture is not user-friendly. It is cumbersome to work with and does not simplify the mission flexibility required in this difficult and challenging flight environment. Any system installed in the aircraft should decrease not increase cockpit workload.

¹Final Report (to be Published), TECOM Project No. 4-AI-190-SOA-014, *Preliminary Airworthiness Evaluation of the MH-47E with Production Compliant Software*.



Figure 1 – MH-47E Chinook and MH-60K Blackhawk²

This thesis will ask the question: What factors caused the incident? Originally, the focus was to evaluate three things: 1) the hardware, 2) the pilot, and 3) the mission to be accomplished. However, as the research progressed, this original focus changed. and a threefold approach emerged: 1) a brief description of the hardware systems directly involved in the incident, yet enough information is provided for a general appreciation of the aircraft's complexity, 2) an examination of the Military Standards/ Specifications applicable to the cockpit displays and instruments, and 3) the results of a task workload analysis pointed toward the factors affecting the incident sequence. The approach provides sufficient detail and analysis to appreciate the problem, yet affords an opportunity to comprehend to complex issues involved in glass cockpit evaluations.

²Reynolds, Paul, U.S. Army Airworthiness Qualification Test Directorate, Edwards AFB, CA

PART 2: BACKGROUND

Since the incident in question occurred in a MH-47E, almost all of the information and descriptions presented are related to that aircraft. However, with the identical cockpit architecture, almost all the discussion in this thesis is applicable to both aircraft.

Mission

The United States Special Operations Command (SOCOM), a specified command, has a National Command Authority mission to conduct unconventional and low-intensity hostile conflict throughout the world. In support of this mission, the United States Army provides helicopter support to the Army Rangers, Special Forces and Navy Seals. SOCOM has a worldwide deployment mission. Their helicopters have to be air-transportable and capable of operations from a variety of water platforms. Missions vary from simple troop transport to airline hijack interdictions, neutralizing hostile open-water oil platforms, and hostage rescue — all of these missions are normally carried out under the protection of night. The Army has used standard UH-60L Blackhawks and CH-47D Chinooks to fulfill this role. Due to the unique aspects of special operations aviation (SOA), the standard Army configured aircraft do not meet this mission requirement. Consequently, the Army has purchased highly modified versions of both airframes. They are the SOA MH-60K and the MH-47E. Under such hostile circumstances, these aircraft are expected to be very flexible in mission capability. As is true in any aircraft design, since the MH-47E and MH-60K are expected to perform a large variety of missions, the design becomes a series of tradeoffs and compromises.

The MH-60K and MH-47E aircraft procurement program was an open bid contract. The contract for both aircraft systems was won by Loral Federal Systems Division, formerly IBM Federal Systems Division. The airframe manufacturers, Sikorsky Aircraft Inc. for the MH-60K and Boeing Commercial Helicopters for the MH-47E, are subcontractors to Loral Federal Systems Division.

PART 3: SYSTEM DESCRIPTION

MH-47E

The MH-47E is a highly modified CH-47D Chinook³. The MH-47E is a twin-engine, all-metal helicopter with a maximum gross weight of 54,000 lbs. The power is supplied by two Lycoming T55-L-714 free-power turbine engines each providing 4,867 shaft horsepower at sea-level, standard day conditions. The engines simultaneously drive two tandem three-bladed, counter rotating intermeshing rotors through engine transmissions, a combining transmission, drive shafting and fore and aft transmissions. The aircraft can carry 36 combat troops internally and external cargo on any of three cargo hooks. The aircraft is equipped with a forward looking infrared (FLIR) sensor, a Multi-Mode Radar and a state-of-the-art avionics' suite (GPS, INS, TACAN, ILS, VOR, ADF, SATCOM, secure communications). A detail description of the MH-47E is contained in Appendix A.

Cockpit Management System

The Cockpit Management System (CMS) is the interface between the crew, the aircraft systems and the Integrated Avionics Subsystem (IAS). The differences between the aircraft (MH-47E vice MH-60K) are the unique power (engine) management systems and the interface to the automatic flight control systems. The aircraft have night vision goggle (NVG) compatible cockpits. The NVGs used by the flight crew are rendered useless by any cockpit lights in the infrared range. The CMS consists of:

1. Four Multi-Function Displays (MFD); one color and one monochrome for each flight station (Figure 2).
2. Two identical center-console mounted Control Display Units (CDU) (Figure 3).
3. Two fully-redundant Mission Processors. These processors control all CMS functions.
4. Two display processors.
5. Two MIL-STD-1553B dual-redundant multiplex data buses connecting the CMS with the aircraft systems.

³Operator's Manual, BH 55-1520-47E (22 October 1992), *Army MH-47E (Prototype) Helicopter*.

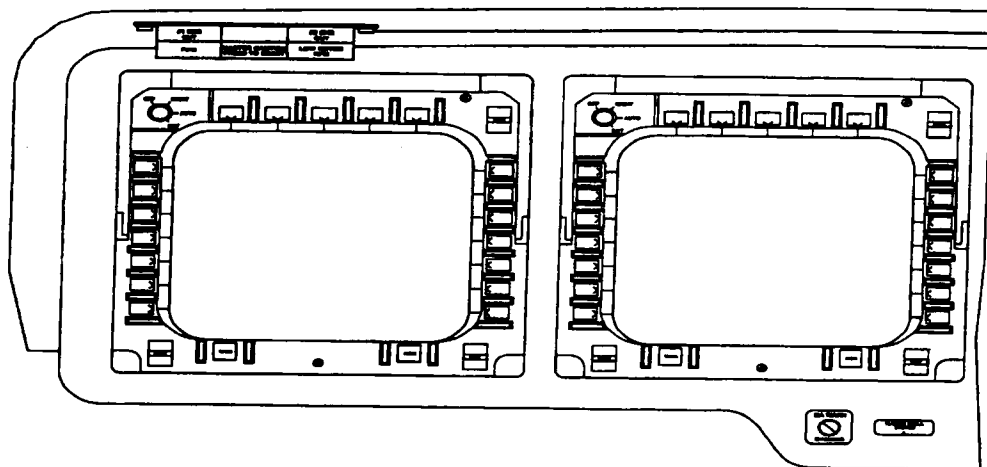


Figure 2 – Monochrome And Color Multi-function Displays⁴

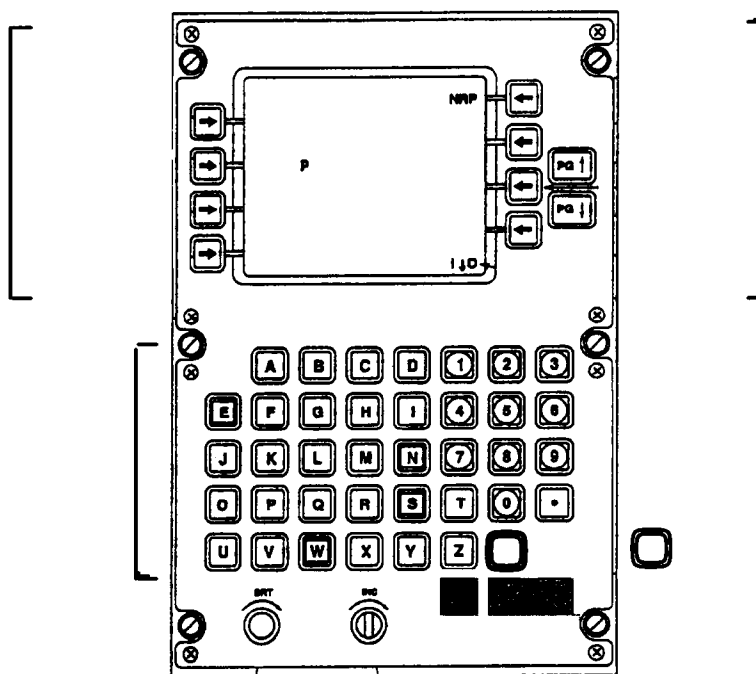


Figure 3 – Control Display Units⁵

⁴MH-47 Pilot/Instructor Pilot AQC, Sikorsky Technical Support Services Training Material, T518038E.

⁵Operator's Manual, BH 55-1520-47E (22 October 1992), Army MH-47E (Prototype) Helicopter, p. 2-1-11.

6. Two Remote Terminal Units. These units connect all non-bus compatible systems to the CMS.

Integrated Avionics Subsystems

The IAS is accessible through two identical center-console mounted CDU and the four MFD. Each pilot has one color and one green monochrome MFD mounted on the instrument panel. The color MFD during NVG operations converts to a green monochrome display.

Multi-Function Displays

The multi-function displays are an integration of information in multiple formats. The displays are 6-inch square cathode ray tube surrounded by a bezel. The MFD display includes various legends next to 19 bezel push buttons (Figure 4). The buttons are vertically aligned along the left and right side as well as along the top of the display.

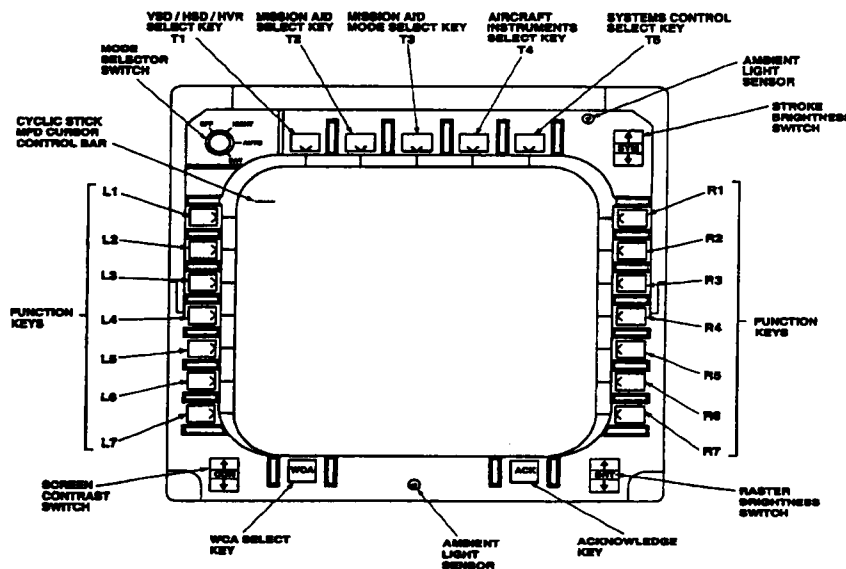


Figure 4 – MFD Color Scheme⁶

⁶Operator's Manual, BH 55-1520-47E (22 October 1992), Army MH-47IE (Prototype) Helicopter, p. 2-2-5

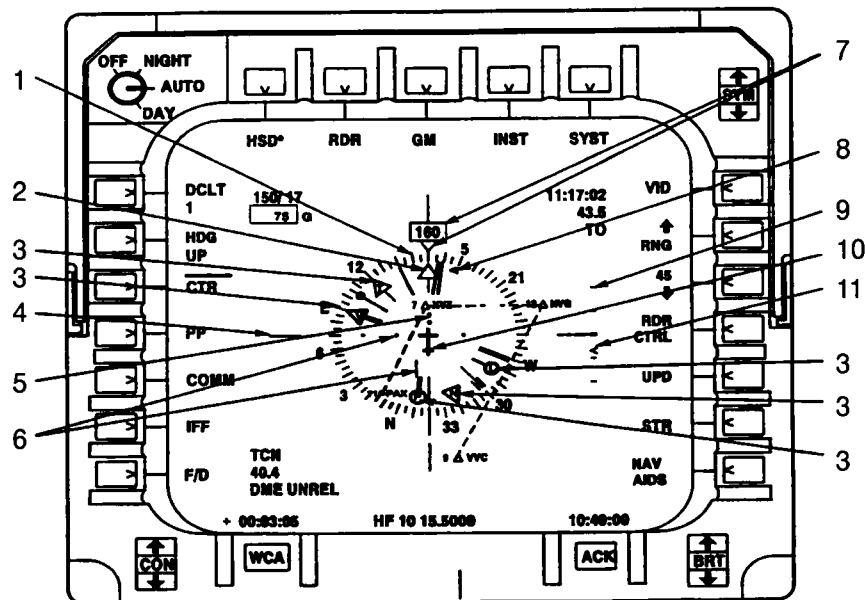
The color MFD, when not operating in the NVG mode, has five colors: green, white, red, yellow and blue on a black background. When the color MFD is in the NVG mode, all displays are in green. The colors shown in Table 1 are designed to aid in pilot situational awareness.

Table 1 – MFD Color Scheme

COLOR	DEFINITIONS
Green	Normal or nominal conditions
White	Advisory messages, some annunciator messages, aircraft reference, attitudes displays, active bezel key display
Red	Warning messages and “out-of-limits” conditions
Yellow	Caution messages and “caution area” conditions
Blue	Sky on the Vertical Situation Display

Horizontal Situation Display (HSD)

The HSD, shown in Figure 5, is a birds-eye view of the aircraft situation. The display center contains a circular compass card. Super-imposed on the compass card are the various selectable needles for: course, TACAN, VOR, course deviation bar, Personnel Locator needle, Navigation Reference Point needle, ADF needle, and other selectable options. There are many other HSD modes. The centered circular compass card can have concentric range rings displayed. The current FLIR sensor azimuth and elevation field-of-regard can be superimposed. Other selectable display possibilities include: winds (direction/speed), groundspeed box, graphical flight plan legs, NRP symbols, “Time-to-Go,” “Distance-to-Go,” TO/FROM indication, threat (display) circles, and recommended ground speed. The HSD can also be de-centered. The center of the compass card is re-located to the bottom of the CRT. The advantage of this de-centered look is to provide better scaling for the situation.



- | | |
|---|--|
| 1. Compass Scale—Circular (Centered only) | 6. Deviation Scale and Bar (Centered only) |
| 2. Course Needle (Centered only) | 7. Heading Box and Pointer |
| 3. HSI Needles (Centered only) | 8. Selected Heading Symbol |
| A=ADF, F= FM homing, | 9. Glideslope Scale |
| V=VOR, T= TACAN, L=LF, P=PLS | 10. Glideslope Pointer |
| 4. Relative Bearing Scale | 11. Airframe Symbol |
| 5. Trend Dots | |

Figure 5 – Horizontal Situation Display⁷

Vertical Situation Display (VSD)

The VSD, shown in Figure 6, is an “out-the-front” look as viewed from the pilot’s perspective. The display is centered on an aircraft symbol. The pitch ladder as well as a bank angle indices provide vertical orientation. Engine Torque is provided in both vertical–tape analog scaling as well as digital format. Barometric altimeter is a digital format. Radar Altitude, when selected, is both vertical–tape analog format and digital readout. The vertical speed indicator is located outboard of the radar altitude display and in vertical–tape analog format. Turn quality information is portrayed by a digital turn–ball and a digital turn needle indicator.

⁷Operator’s Manual, BH 55-1520-47E (22 October 1992), *Army MH-47E (Prototype) Helicopter*, p. 2-15-13.

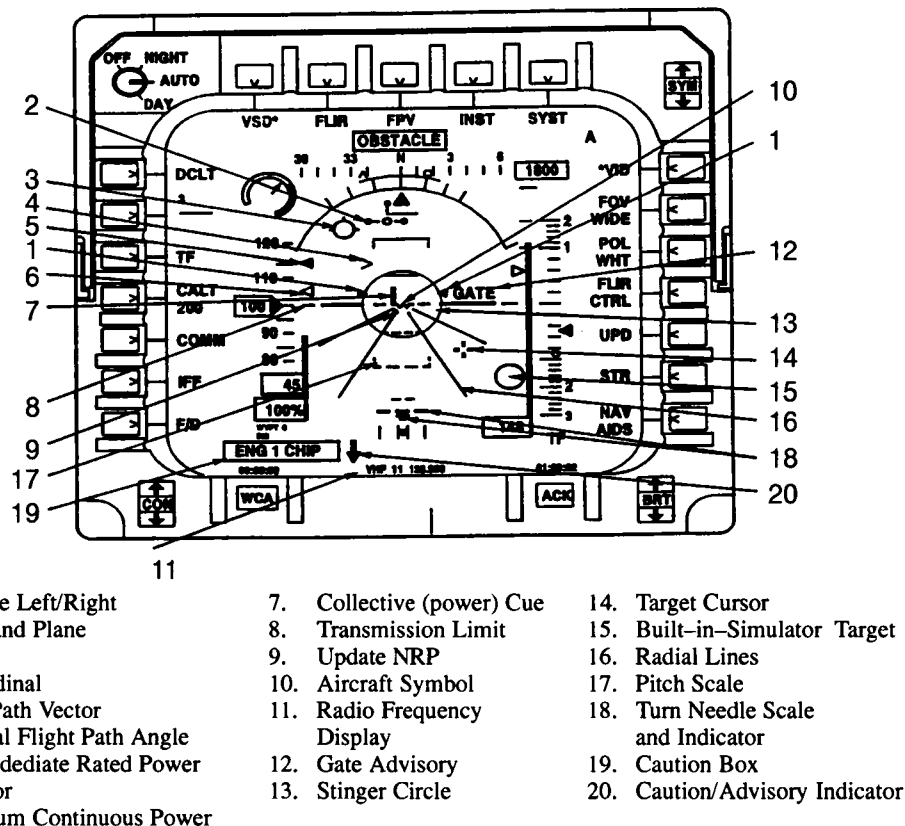


Figure 6 – Vertical Situation Display⁸

Multi-Function Displays Layering

The MFD have multiple layers to access the various functions (Flight Plan Legs, Checklist Menu Page, etc. pages) and other systems (FLIR, Multi-Mode Radar, Digital Map). The normal configuration is for the flying pilot to configure with the Horizontal Situation Display (Figure 5) on one MFD and to have the Vertical Situation Display (Figure 6) on the other display. It is possible to have other systems or sensors integrated on to one or both MFDs. A typical configuration might be the digital map or FLIR as an underlay to the VSD or HSD. The MFDs also have a hierarchical system in case of a MFD failure. There is an embedded logic to aid in pilot situational awareness.

⁸Operator's Manual, BH 55-1520-47E (22 October 1992), *Army MH-47E (Prototype) Helicopter*, p. 2-15-6.

Once into the MFD sub-layers (Figure 7), there are as few as one layer for the check list menu page and as many as 100 pages for the flight plan system.

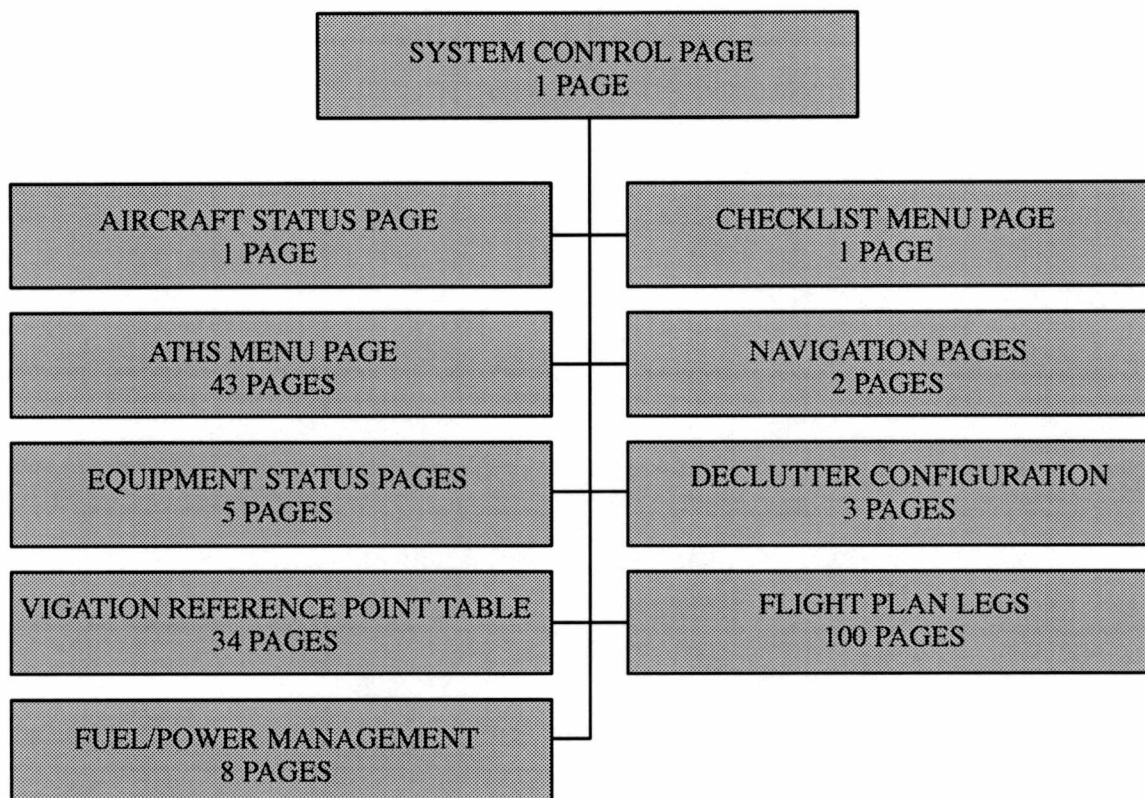


Figure 7 – MFD Sub-system Page Layering

Test Character Size

Text character size varies within the MFD. The six-by-six-inch display is divided into various fields on the CRT display circumference. The top bezel pushbuttons have five 5-character fields. Directly underneath this field is the *Warnings* field. The *Warnings* field is a double row with twenty characters per row. The left and right bezel pushbuttons, seven on the left and seven on the right, have individual identification fields. Each pushbutton has an individual identification field containing three 5-character rows. The *Annunciator* field is a symmetrically divided three-row pattern. The top two rows are each 15 characters wide with the bottom row having 17 characters. Underneath the *Annunciator* field is the *Cautions* field. This is also a divided symmetrical pattern.

Although a single row, each half of the field is 20 characters wide. Finally, underneath the *Cautions* field is the *Operator Alert Message Area*. This is a single field with a 22-character width.

Warning and Caution and Advisory System

The Warning, Caution and Advisory system (WCA) provides the crew with visual feedback, via the MFDs, to an aircraft/aircraft system condition fault or problem (Figure 8). The WCA system categories are shown in Table 2.

Table 2 – WCA Definitions

<i>Warnings</i>	Situations that require immediate crew action to prevent death or injury
<i>Cautions</i>	Situations which require operator action to avoid or reduce equipment damage or preclude the condition from becoming a Warning
<i>Advisories</i>	System or mission equipment limitation exists which may require crew attention

Warnings are presented in a flashing visual text format on the MFD. Illumination of a Warning also illuminates the Master Caution Light. The Master Caution Light can be extinguished by depressing the light or use of a cyclic-mounted switch; however, the flashing Warning message will continue to flash. Some Warnings are also relayed to the crew via a Voice Warning System. Cautions and Advisories are also presented in flashing visual text format on the MFD. These messages can be acknowledged via a pushbutton on the MFD or a cyclic mounted switch. Once acknowledged, these messages cease to flash. All WCA messages are on a prioritization protocol. This allows for lower urgency messages to be displaced by more immediate messages. The WCA system contains 322 separate messages.

Voice Warning System

To enhance crew situational awareness and supplement the WCA, auditory warnings are provided. The Voice Warning System (VWS) contacts the crew via the inter-communications system. There are 10 VWS on a prioritized system. Similar to the WCA, these messages can be acknowledged via a bezel pushbutton on the MFD or a cyclic-mounted switch.

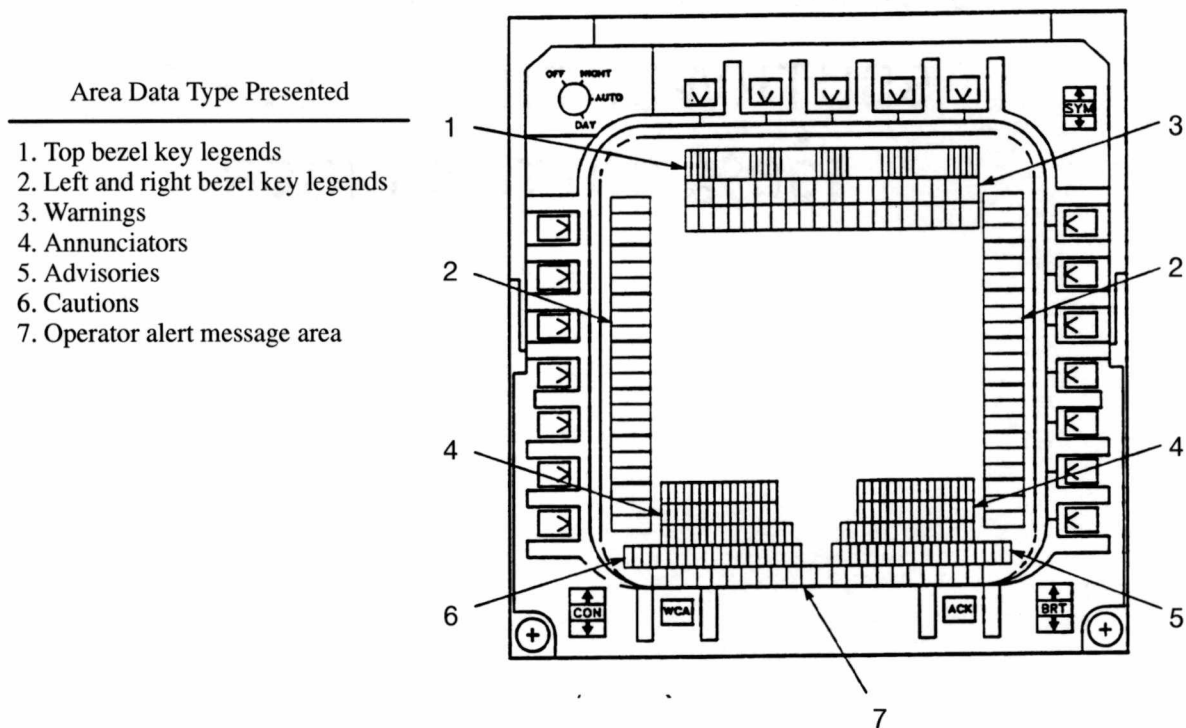


Figure 8 – MFD Warning, Caution And Advisory Fields⁹

⁹Operator's Manual, BH 55-1520-47E (22 October 1992), Army MH-47E (Prototype) Helicopter, p. 2-2-3.

PART 4: INCIDENT SEQUENCE ANALYSIS

GENERAL

The tactical navigation (TNAV) system is capable of computing/generating an approach and then executing a coupled approach. The intended landing point can be established several ways. During the incident approach, the intended landing point had been entered into the IAS as latitude and longitude coordinates. The TNAV system now was using the intended landing point as the final way point on a low-level navigation route. The final waypoint happened to be over water.

The final waypoint/intended landing point was over-flown. The aircraft then started a right turn to enter the down-wind leg and initiated a descent. Based on the previously programmed data, the IAS automatically assumed that the termination of the approach was to a captured radar altitude automatic hover hold. However, during the maneuver the co-pilot announced and deselected the radar altitude capture. The pilot flying the aircraft stated he did not hear the deselection announcement. A post-flight review of the MFD video and cockpit audio clearly establishes that the announcement was made and that the Annunciator did show a flashing annunciation signalling to the crew that the radar altitude capture had been disengaged. The pilot clearly was surprised when the aircraft descended through 50 feet. The pilot quickly reacted and with a large, over 100% dual-engine torque, power application stopped the aircraft with the aft wheels within 5 feet of the water.

PILOT EXPECTATION

Pilot expectation is that characteristic that exists when a situation has an assumed outcome. The expectation is based on repetition, which is a skill-based behavior¹⁰. A more dangerous and insidious cause is that the pilot never comprehends a change or recognizes that new information requires a reevaluation of the situation. People are creatures of habit. How many times have each of us driven to work, pre-occupied or day-dreaming, and suddenly realized we do not recall driving to work?

¹⁰Goodstein, L.P., Anderson, H.B., Olsen, S.E. (1988), *Tasks, Errors and Mental Models*, Taylor & Francis: London, Philadelphia, p. 230

Appendix B contains a broad structure outline for analysis of a "system."¹¹ This is broad-based analysis for use with incidents involving human malfunction referred to in literature as Human Reliability Analysis (HRA)¹². Here our system is a helicopter flying task that nearly ended as a catastrophic accident. In using the HRA outline, if the situation is applicable, then it is discussed in the following paragraphs; if not, then that subject is skipped. Our system has a machine/systems (the MH-47E Chinook), an operator, and a task (the coupled navigation to a radar altitude captured hover over water).

FACTORS AFFECTING PERFORMANCE

Subjective Goals and Intentions

The system's goal is to safely navigate the helicopter to a precise point, have the helicopter execute an approach that terminates in a 50-foot hover over the water and then accurately holds that hover position. By design, the intention is that the only pilot/crew interface with the IAS is to program it and respond to any malfunctions. Ideally, this is a totally (pilot) hands-off sequence. To be more detailed, the IAS is supposed to: a) hold airspeed within 5 knots, b) altitude within 20 feet enroute, c) course within 100 meters, d) initiate the approach, e) initiate the hover, f) have computed the power required to hover to keep from demanding more power than available, g) captured the hover, h) terminate the hover and i) hold hover altitude/position. Does the pilot monitor this constantly? Ideally — yes. Realistically, he monitors only those critical phases based upon available time (division of attention).

Mental Load

System Initialization

The pilot is under a tremendous mental load. He is the critical link for all functions. All data (frequencies, waypoints, secure communications codes, IFF codes) used by the IAS, with exception

¹¹Wilson, J.E. & Corlett, E.N. (editors) (1990), *Evaluation of Human Work*, Taylor & Francis: London, Philadelphia, p. 774

¹²Goodstein, L.P., Anderson, H.B., Olsen, S.E. (1988), *Tasks, Errors and Mental Models*, Taylor & Francis: London, Philadelphia, p. 203

of the SATCOM, ground VHF and the High Frequency radios, are loaded via the CDU and selected from the MFD. Pilots can load portions of the mission information through a pre-loaded data cartridge. However, it is still only as accurate as the pilot input. The Attitude and Heading Reference System (AHRS) and the Inertial Navigation Unit both require manual input for present position information (latitude/longitude) before ground alignment.

The AHRS is turned ON/OFF from the MFD equipment status page. The AHRS has several notes, cautions and warnings throughout the MH-47E Operator's Manual highlighting some of the following areas. A potentially disastrous error source for the AHRS is premature selection of the navigation (NAV) mode. As the AHRS ground aligns, the compass card slowly rotates to a position 180 degrees from the actual aircraft heading. This alignment protocol is the same for all AHRS systems (AH-64 & OH-58D(I)). Then after about eight minutes, with the AHRS aligned, the compass card rotates back to the actual aircraft heading. If the pilot was in a hurry and selects the NAV mode on the AHRS, as in a real-world mission, the consequence is that all longitudes/latitudes and vertical velocities are reversed. This error becomes compounded since AHRS data is used for computation of vertical velocities, ground speed, wind direction and speed, display of navigation reference points (NRP), trend dots on tactical navigation displays and the Horizontal Situation Display. The AHRS cannot ground align if the SEA Mode (as in the ocean) has been selected on the MFD navigation control page. (Remember, the AHRS ON/OFF control is on a different MFD page.) The navigation control layer is not normally used during the run-up nor is this a checklist item. This mistake could easily occur if the last mission was over-water or the mission terminated to a ship.

Navigation Reference Points

The pilots manually enter the navigation information for the IAS. To load each NRP requires manual keypad input. Each NRP contains the following: leg number or source/destination, leg type, leg altitude, wind and Outside Air Temperature, Minimum Safe Altitude/Emergency Safe Altitude, time and speed override values (if you are behind on the mission, which parameter is more important), course, NRP comments, fuel change and cargo hook weights. The IAS is capable of 100

NRP. There are 16 different steps to load each NRP. The 16 different steps are divided between the center console's CDU and the MFD. This would be somewhat similar to programming a VCR with the remote control on the table and 19 buttons around the edge of the TV. Now imagine that someone is shaking the chair while the programmer is trying to read a map or the TV guide while trying to accomplish this task. The system input software is not easy to work with. If one enters a latitude or longitude wrong (forget to use zeros or put East instead of West) it cannot help. There are no imbedded smart instructions or logics to preclude data input error. Consider the following scenario: it is now 3:30 a.m., the aircraft has just picked up some "good guys" in hostile territory, the AWACS has just radioed (secure) that the egress route now has an active radar and suggests using an "alternate route." Now a mission change is required and an update to the navigation information.

Tactical Situation Awareness

The mental load is just beginning. The return mission still has to be flown. There are decisions as to how the navigation information is to be used in the Tactical Navigation or Electronic Navigation Mode such as whether to use heading hold, course hold, vertical climb, radar altitude hold, ground, equivalent or indicated airspeed hold, barometric altitude holds, and others. These decisions are or can be affected by enemy situation. If the mission is to be under emissions control (EMCON), then nothing can transmit a source signal/radar. This means no radar altimeter, no missile warning jammers, no multi-mode terrain following radar, no Identification Friend or Foe (IFF) transponders, just to name of few systems. The loss of a UH-60, shot down in Iraq by F-15s, was a result of an error in use of the IFF transponder. It turns out that the UH-60 operator's manual was poorly written and ambiguous as to the various modes for the IFF.¹³ The result — many lives lost.

There is not sufficient time to completely deal with every potential problem with the IAS and its associated systems. The facts are that the IAS is too complicated and not user-friendly. The pilots flying the mission are responsible for everything. The USAF MC-130 Combat Talon II uses the

¹³Electronic Message (081724Z NOV 94), Commander Aviation and Troop Command, AMSAT-X, subject: *AN/APX-100(V) USER ALERT*; reference: *AIR FORCE INVESTIGATION INTO F-15 SHOOTDOWN OF UH-60 HELICOPTERS*.

same "glass cockpit" architecture. The USAF has a navigator and electronic warfare officer on board to handle all the IAS data entry. All the pilots do is fly.

SYSTEM RESOURCES

In analyzing this system four items are part of the system resources: training (initial and recurrent), checklists, simulators and imbedded smart designs and fault blocks. All MH-47E pilots are CH-47D rated prior to MH-47E training. Initial qualification training for the MH-47E is a ten-week course. By far the bulk of classroom training (4 weeks) is on the IAS. Two weeks are on aircraft systems (transmissions, engines, etc.) and four weeks are for accumulating 40 hours of flight and simulator time. The simulator is a good tool. It provides a two-fold benefit: first it can be used for recurrent training, and second, it can be used for mission rehearsals for difficult or complex tasks. From a macro level, this training would appear to be more than adequate. However, if the four weeks of MH-47E IAS training is compared to current "glass-cockpit" transport category cockpit management system training — the 160 hours is about the same. The MD-11 series pilots spend an average **160 hours** learning about managing and navigating with various systems (VOR, TACAN, GPS, ILS) and flying at high altitudes.¹⁴ The MH-47E pilots spend 16 hours on the equivalent equipment (VOR, TACAN, GPS, ILS) called the Electronic Navigation (ENAV) system. The ENAV system is every bit as complex as any transport category "glass cockpit." By comparison the MH-47E pilot gets only 10% of the training by comparison to his transport counterpart.

The aircraft checklists are woefully inadequate. There are 322 separate warning, caution and annunciator messages programmed into the IAS. The Airborne Target Handover System (ATHS) has 43 MFD pages to transmit messages with 250 abbreviated text words. The amounts of information the pilots are required to assimilate and interact with is staggering.

¹⁴Dornheim, M. A. (November 23, 1992), "CHANGES HIKE MD-11 TRAINING SUCCESS," *Aviation Week & Space Technology*, pp. 93-95.

The fact that the information is available within the operators manual is not good enough. The information must be readily accessible and easily discernable. The pilot must be able to find exactly what he needs immediately — this means within seconds.

SITUATION FACTORS

Task Characteristics

An area that has received much press lately is the area of mode switching.¹⁵ In the incident scenario, this refers to the mode switch from coupled autopilot TNAV to a coupled radar altitude hover hold. During an anticipated mode switch two monitoring tasks must be accomplished. First is the TNAV flight director cues, insuring that the autopilot is properly following/flying the cues. The other mode is the capture of the auto-hover. The auto-hover capture is initiated by a descent then a deceleration to the hover. This entails the crew monitoring not only the displays of the HSD but the flight director cues, mode switching and engine power margins.

The task was to fly a coupled TNAV route to a coupled radar altitude hover hold. The crew (pilot and copilot) had to monitor the aircraft states, maintain see-and-avoid visual flight rules clearance, insure correct airspeed, correct altitude, and radio monitoring. The TNAV MFD display provides trend dots that graphically portray the future aircraft flight path on the HSD. Each dot represents a five-second anticipated flight path. This display is normally layered on top of the FLIR display so that the intended landing point is viewable. The last NRP was the initialization point for the coupled automatic hover. The crew had selected barometric altitude hold to maintain a constant altitude. However, the aircraft was flying at around 500 feet above the ground. The crew had to monitor that the barometric altitude hold was operating normally. Due to the aircraft's high gross weight, high temperature and humidity the power margin between the power available and power required continuous crew-monitoring. The workload for the crew was high. They were in close proximity to the ground, at high gross weight with diminished power margins, and having to monitor the flight director and flight director mode switch.

¹⁵Hughes, D. et al (January 20 & February 6, 1995), "AUTOMATED COCKPITS SPECIAL REPORTS, PART I/II," *Aviation Week & Space Technology*, pp. 52-65/48-57.

Physical Environment

The MH-47E Chinook cockpit is a very hostile environment. The cockpit has a 5-plate windscreen arrangement. In sunny conditions, the large glass cockpit areas create a greenhouse effect on the pilots. Each pilot also has a chin bubble for ground reference. The only ventilation is the cockpit ram-air system and the windows. This system is inadequate when the crew is wearing survival vest, body armor or dry suits for overwater flights.

The cockpit is located just in front of the forward transmission. This close proximity subjects the crew to both high-frequency noise and medium-frequency vibrations. In fact, the airframe tuneable vibration absorber is located just forward of the instrument panel. The MH-47E ambient cockpit noise level is 120 dB.¹⁶ A pilot with a properly fitted flight helmet and foam-core ear plugs cannot get the noise level reduced to a non-injurious level (65 dB).

Additionally, the intercommunication's system (ICS) is inundated by a high-pitch hum from the 115/200 VAC generators. This high-pitch hum is oppressive making basic inter-cockpit communications and conversing with the cargo compartment crew very difficult. To understand basic speech, the ICS volume levels must be turned UP to an inordinately high level to overcome the high-pitch hum. With the complexity of the IAS, inter-crew voice communications is imperative. This means that the crew is constantly subjected to not only high-volume noise, but high-frequency noise as well. This type of stress takes its toll on the crew in the form of fatigue.

WORK TIME CHARACTERISTICS

Many studies have produced data as to the significance of biorythms and circadian rhythm cycles.¹⁷ This is particularly significant considering the Special Operations Forces (SOF) mission. The SOF want to have the opportunity to perform their mission under the cover of darkness. This means the take-off time for missions is normally late, after 9 p.m. Mission duration is dependent on the task. To appreciate the SOF mission, there is a need to work backwards in terms of when to attack

¹⁶Department of the Army (May 1987), *Aeromedical Training for Flight Personnel*, Field Manual 1-301.

¹⁷Orem & Barnes (editors) (1980), "ChronoCare™ Action Plan," Adapted from *Physiology In Sleep*, Academic Press, pp. 7-9.

or surprise an enemy. The lowest level of human activity and the best time for surprise is 3 a.m. to 5 a.m. But, this lull in performance is also true of the flight crews. Consequently, the very nature of the SOF mission is to accomplish it at the point where human performance is at its worst. The significance is that the aircraft systems should be optimized for the reduced level of human performance. On the contrary, these systems require even more attention than should be considered normal. Therefore, a very real concern that the MH-47E helicopter IAS (as a total system) is more of a deterrent to accomplishing the mission than an aid.

PART 5: SPECIFICATION COMPLIANCE

GENERAL

Clearly, more than a pilot missing a cockpit announcement and flashing annunciator caused the scenario. Several factors contributed to this event. Among these were workload, MFD displays, annunciator depiction, display format and data display. A thorough review of data and literature was conducted to examine the compliance issue. A list of data (Military Standards, Military Specifications, NASA Technical Notes) is shown in the Appendix C. Each of the referenced documents was reviewed and compliance/non-compliance determined. To say, specification compliance is lacking, would be petty. It would be fair to conclude that some basic guidelines, as outlined in various authority documents, have been ignored or disregarded.

AIRCREW STATION CONTROLS AND DISPLAYS FOR ROTARY WING AIRCRAFT

The Standard¹⁸ is not complied with in several ways. The MFDs are in a side-by-side arrangement. This arrangement violates the traditional "T" arrangement historically used in aircraft cockpits. The information from the old style cockpits is still available but in different locations and presentations. Every Electronic Flight Instrument System (EFIS) reviewed showed the aircraft attitude display oriented on the instrument panel above the compass card (horizontal situation) display. Even the use of one display (CRT) for a miniaturized presentation had the attitude indicator vertically aligned and above the compass card display. The review of literature showed no information relating to the problems of a side-by-side presentation. There appears to be no compelling reason to alter the conventional display. Colloquially— if it isn't broken, don't fix it.

The aircraft status page containing all the primary aircraft system information can be accessed only by the pilot calling it up. The current IAS architecture violates the Standard, in that the status of primary aircraft systems (engines, transmissions, etc.) are not readily displayed.

¹⁸Military Standard (30 Sep 1988), *Aircrew Station Controls and Displays for Rotary Wing Aircraft*, (MIL-STD-250D).

AIRCREW STATION ALERTING SYSTEMS

The Standard¹⁹ requires that *Cautions* be in a yellow display and *Warnings* in red. The nature of an NVG compatible cockpit precludes this. The attendant risk of pilots not noticing a *Caution* or *Warning* is self-evident.

The Standard requires that an Alerting System: *shall provide visual alerts which can be detected and understood easily under . . . critical (i.e., high workload, high stress, low light level) conditions.* The MH-47E normally flies at or near maximum gross weight. As such, in warm (+20°C) conditions, the engine torques are always transiting in and around the 100% mark. The IAS, based on ambient conditions and a series of unverified performance look-up tables, computes the maximum torque available. If the pilot is demanding power in an avoid area the VSD digital torque display flashes. The consequence of this is that the pilot become de-sensitized to a flashing display since it occurs so frequently in this flight environment. This de-sensitization was a causal factor in the incident. The test pilot, desensitized to the “flashing” display, failed to cognitively recognize the flashing radar altimeter decoupled (RALT DCPLD) annunciation.

LEGENDS FOR USE IN AIRCREW STATIONS AND ON AIRBORNE EQUIPMENT

There are several instances of non-compliance with the Standard²⁰ for syntax in the *Warnings, Cautions and Advisories (WCA)*. There are tables that establish the preferred syntax for various words or word groups. The most glaring problem is the inconsistency in application of numerical designation. Sometimes the “#” is used, in others “No” is used and finally, there are cases where the number is used after the noun identifier “ENG1.” The purpose of syntax is to train the mind to process information in a repeatable systematic fashion. The use of three different formats serves only to confuse the pilot. Another syntax issue is the non-standard abbreviations. In reviewing the 322 WCAs, it is obvious that the designer took license to change (shorten) abbreviations when messages were too long to fit in the appropriated WCA fields.

¹⁹Military Standard (31 Mar 1991), *Aircrew Station Alerting Systems*, (MIL-STD-411E).

²⁰Military Standard (18 Dec 1984), *Legends for Use in Aircrew Station and on Airborne Equipment*, (MIL-STD-783D).

ELECTRONICALLY OR OPTICALLY GENERATED DISPLAYS FOR AIRCRAFT CONTROL AND COMBAT CUE INFORMATION

The attitude indicator is portrayed on the HSD (Figure 5). The HSD pitch ladder is not numerically indexed. The Standard²¹ requires that aircraft pitch attitude indicators/instruments display digital numerals along/adjacent to the pitch ladder. The MH-47E ground school reference manuals show the pitch ladder with numerals. The HSD radar altitude display has a digital numerical display that is shown at the top of the altitude ladder. The Standard requires that the numerical readout be displayed at the bottom of the ladder. The HSD bank angle indicator reference is a "sky" pointer as opposed to the conventional "earth pointer." The standby attitude indicator is opposite the HSD display. This creates a problem with the pilot having two opposite bank attitude indicators in the cockpit. Pilots, during the fight test program, often ignored the HSD display in favor of the conventional standby attitude indicator. A sad commentary that a sophisticated glass cockpit is ignored in favor of older-generation "steam-driven" gauges.

HUMAN FACTORS ENGINEERING DESIGN CRITERIA FOR HELICOPTER COCKPIT ELECTRO-OPTICAL DISPLAY SYMBOLOGY

During NVG operations both MFDs will be green monochrome displays. The Standard²² requires that the sky and ground, as depicted on the attitude indicator show the ground as shaded for horizon reference. The manufacturer's design problem here is that it would be impracticable to layer the FLIR or digital map underneath the HSD with shaded ground. However, it would be an easy software fix to display the ground shading unless it layered with the FLIR or digital map and, if so, remove the ground shading. The heading tape to display the aircraft magnetic heading is a thin tape providing ten-degree indices and five-degree sub-indices located above the pitch ladder. The actual aircraft heading is a three-digit numerical display centered above the moving tape display. The Standard requires the heading tape to cover a large physical area and be displayed at the physical top of the CRT display. As shown on the HSD in Figure 5, the standard is not complied with.

²¹Military Standard (25 Apr 1975), *Electronically or Optically Generated Displays for Aircraft Control and Combat Cue Information*, (MIL-STD-884C).

²²Military Standard (30 Jun 1984), *Human Factors Engineering Design Criteria for Helicopter Cockpit Electro-Optical Display Symbolology*, (MIL-STD-1295A).

Additionally, the aircraft heading is required to be referenced by a vertical line affixed to the heading tape. There is no vertical line on the display.

The final point from this Standard is that the airspeed display can be indicated, true or ground speed. It is possible to select and display on the HSD calibrated air speed (CAS). This is not really a problem in terms of being erroneous or wrong information unless the pilot incorrectly or inadvertently selects CAS. It is difficult to imagine a requirement or situation that would require the operational pilot to need CAS.

HUMAN FACTORS ENGINEERING DESIGN CRITERIA FOR MILITARY SYSTEMS, EQUIPMENT, AND FACILITIES

To help highlight the IAS problems, the identified problem is in italics and the conflict or non-compliance to the Standard²³ is in normal print. *The VSD attitude indicator and the standby attitude indicator are opposite sensed— one is an earth pointer and the other a sky pointer.* The Standard states that controls and display shall be unambiguous. Two opposite sensing primary flight instruments violates this guidance.

In case of an engine malfunction, there is no embedded MFD logic to bring up the power management (engines) display automatically to aid the pilots. To access the power management page (display) the pilots have two options. First, they can pre-position the floating cursor on the MFD bezel button array to the T4 button and by depressing the cyclic-mounted button, access the engine display. The other method is reach up and manually depress the T4 button. The Standard requires that "Emergency Displays" shall be located where they can be seen and reached with minimum delay. The V-22 Osprey is equipped with the same Loral IAS system as the MH-47E. The V-22 accident at Quantico, VA where the Boeing pilot scrolled through 22 different MFD screens in the final 17 seconds is testimony that an embedded system is required. The V-22, at the USMC's insistence, will have a fifth MFD dedicated to engine and power train information.²⁴

²³Military Standard (14 Mar 1989), *Human Engineering Design Criteria for Military Systems, Equipment and Facilities*, (MIL-STD-1472D).

²⁴Price, LTC Richard, USMC (April 1994), *Interview*, Deputy Director V-22 Combined Test Team (USMC/Bell/Boeing).

The only MFD depiction of barometric altitude is digital. According to the Standard, a numerical display shall not be the only display. The Army experimental test pilot was unable, using the digital display, to fly a constant altitude within plus or minus 20 feet. The lack of rate information, normally provided by the counter-drum analog barometric altimeter, makes flying constant altitude impossible. The only way to fly constant altitude in the MH-47E is to use the flight director with a coupled autopilot or use the standby altimeter.

The MH-47E is equipped with a unique inter-communications systems to insure compatibility with the secure voice communications radios. The ICS is called a TEMPEST compatible system. The ICS system is inundated by the high frequency generator hum. The Standard requires that any environment that has a high noise level (in excess of 100 dB overall) have noise cancelling microphones installed. The MH-47E is documented to have noise levels at 120 dB. There are no noise-canceling microphones or any special systems installed to meet the Standard's requirements.

These four deficiencies only highlight the non-compliance issues related to the MH-47E.

TASK PERFORMANCE ANALYSIS

The Standard²⁵ requires that each task performed by operating a system, here a helicopter, have an in-depth analysis conducted. Such tasks would have to encompass hovering, hovering turns, takeoff, landing, etc. This task analysis includes such items as: task criticality, identification of human errors, and sensory or cognitive overload, body disorientation, sustained or continuous operations. The next step required is an analysis of task Input Parameters (information required/available, initiating cues, data display format). The next analysis step is determining the operator feedback required. The ambient conditions (temperature, ventilation, ambient lighting) where the task is to be accomplished require evaluation. The MH-60K and MH-47E have been flying for five years. The MH-47E is now fielded and performing real-world hostile missions. To date, the Task Performance Inventory has not been accomplished. In addition, the Standard requires that a task standard be established. This task standard will have an estimate of the probability of error

²⁵Military Standard (13 May 1991), *Task Performance Analysis*, (MIL-STD-1478).

as a function of aptitude (operator) and training, and an estimate of the time period for operator to demonstrate successful performance.

DESIGN AND CONFIGURATION OF MARKINGS FOR AIRCREW DISPLAYS

The numerical and character size and font on the MFD and CPU do not conform to the Specification.²⁶ The HSD circular compass scale has the numerals displayed on the outside of the compass rather than on the inside. The fonts used on the various MFDs are not the fonts called out in the Specification. The correct font is not used to save space on the MFD. The result is words that have been truncated. The truncated text is not as readily understood by the pilots. The MFDs have several digital displays that have no analog displays. The consequence of this is that numbers that should be easily understood at a single glance require a dedicated effort to determine the information. Saunders²⁷ concludes that one causal factor in a USMC F-18 accident was “. . . Foveal vision concentrating on (a) digital airspeed (display) required cognitive attention until (the pilot was) satisfied with airspeed, . . .” This well-trained USMC pilot had to spend an inordinate amount of time concentrating on a digital display. This momentary delay in his instrument cross-check initiated the sequence of events resulting in the total loss of a multi-million dollar aircraft.

HUMAN ENGINEERING REQUIREMENTS FOR MILITARY SYSTEM, EQUIPMENT, AND FACILITIES

There are several systems engineering requirements required by the Standard²⁸ that must be presented to the procuring agency. Among these are to prepare operationally realistic mission profiles and scenarios. In establishing these mission scenarios, the contractor is to prepare functional flow block diagrams. These diagrams are to show the: start, process, decision points, options and the event culmination. During the block diagram preparation, all training implications regarding the mission scenarios have to be identified. Commensurate with this is a requirement for access to all the

²⁶Military Specification (15 Mar 1989), *Markings for Aircrew Displays, Design and Configuration of*, (MIL-M-18012B).

²⁷Saunders, F.(July, August, September 1989), *Cobra-in-the-Basket: What You Don't See Can Kill You*, COCKPIT, Journal of the Society of Experimental Test Pilots, pp 4-12.

²⁸Military Standard (26 May 1994), *Human Engineering Design Criteria for Military Systems, Equipment and Facilities*, (MIL-STD-46855).

data used to accomplish the human engineering system aspects. The data have yet to be submitted to the procuring activity. All identified critical tasks require analysis. The critical task analysis entails an examination of the information required by the operator, the body movements required, feedback to the operator, operator/crew member interactions and the performance limits on personnel. The workload analysis requires a detailed operational mission sequence, the amount of time devoted to sub-tasks, workload, mental effort and psychological effects. A further analysis of the work environment is required. The work environment evaluation should look at factors such as atmospheric considerations, range of accelerations, acoustic noise, and minimization of disorientation. It cannot be said that the required analyses have not been done. What can be said is if they have been done, nobody within the Department of Defense or the contractor (Loral) has the results.

PART 6: CONCLUSIONS

GENERAL

The overly complicated and poorly designed integrated avionics subsystem (IAS) installed in the MH-47E was a causal factor in the near accident.

SPECIFIC

The poor IAS design and implementation is caused by the designer and manufacturer failing to follow established guidelines as outlined in the Military Standards and Specifications. The companies will further contend that the requirements do not pertain or apply to their systems. This incident was precipitated by the violations of the intent of the applicable Standards and Specifications.

The MFD design is cluttered and needlessly "busy." It is further concluded that the cockpit integration violates the intent of any aircraft enhancement. Any enhancement to an aircraft system (helicopter and/or pilot) should reduce the pilot workload by either off-loading tasks or automating functions. It is apparent that systems and controls have been automated or integrated within the IAS just because the technology permitted it.

The opposite and reversed-sense roll/bank attitude indicators that create pilot confusion are a major deficiency. The lack of a primary-flight analog barometric altimeter display is a major deficiency.

The obvious lack of system analysis by the designer is considered a causal factor. The lack of a system engineering breakdown of critical flight tasks, specifically mode switching is a major deficiency. The implications of the system engineering deficiencies include the lack of crew coordination, pilot workload, pilot situational awareness and crew excess capacity versus workload saturation.

Finally, the US Special Operations Command is faulted for expecting this aircraft/pilot system to be capable of performing all the missions envisioned. The missions are very difficult and demanding. The crews to perform these tasks, require equipment that is straight-forward, unambiguous and easy to operate. The MH-47E is too complicated and crews will never fully understand the systems due to the shear volume of information and complexity.

This thesis has concluded that the MH-47E incident was caused by:

1. poor design,
2. non-compliance with the intent and criteria established in Military Standards and Specifications,
3. poor system analysis, and
4. an overly ambitious program.

PART 7: RECOMMENDATIONS

There are two possible recommendations to fix the Integrated Avionics Sub-system. The first would be to start all over from the beginning. This approach, although appearing to be possible, is fiscally and politically not possible. The second approach is to fix what can be fixed and continue to improve the IAS and its components. The later approach has the best possibility of success. A carefully thought out plan is the most realistic.

The Special Operations community is extremely territorial. It is their opinion that they are the only ones that can possibly know and evaluate (test) their aircraft. What is missing from their logic is that test organizations live in the world of the unbiased. We are trained observers taught to be detached from what we test.

The IAS can be fixed. Prioritize the display problems. They can be fixed with little impact on the overall IAS architecture. This approach will reduce the required amount of regression testing. Limit the tactical employment of the more exotic modes until more flight time is accumulated on the systems. Finally, keep the testers in the process as software is revised. They will do a better job of keeping configuration control and asking the contractors the hard questions. A rigorous testing discipline is the only way to insure a safe system.

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APPENDIXES

APPENDIX A

SYSTEM DESCRIPTION

MH-47E

The MH-47E is a twin-turbine-engine tandem rotor helicopter design for to meet several missions: special operations (conventional and unconventional), transportation of cargo, troops, and weapons. The aircraft is capable of operations in day, night, visual, and instrument conditions. The MH-47E is equipped with a fixed aerial refueling boom for refueling from C/HC/MC/KC-130 aerial tankers aircraft. The power is supplied by two Lycoming T55-L-714 free-power turbine engines each providing 4,867 shaft horsepower at sea level standard day conditions. The engines simultaneously drive two tandem three-bladed, counter rotating intermeshing rotors through engine transmissions, a combining transmission, drive shafting and fore and aft transmissions. To facilitate aircraft main engine starting and pre-start checks with rotors stopped, a gas-turbine auxiliary power unit is installed behind the aft transmission in the aft pylon. The APU drives a generator and hydraulic pump for ground operations. The MH-47E has two large sponson-type 1000-gallon waist-mounted fuel cells. The aircraft incorporates four fixed-type wheeled landing gear. The aft right landing gear incorporates a power steering unit for ground operations. The MH-47E is water capable and uses the power steering as a quasi-rudder. The maximum gross weight is 54,000 lbs.

The aircraft is capable of carrying 36 combat troops internally and external cargo on any of three cargo hooks. The three-hook configuration is unique for helicopters. The center hook is accessible from a floor access panel in the internal cargo compartment. The forward and aft hooks allow non-aerodynamic loads to be stabilized for high-speed low-level transport.

The aircraft is equipped with a forward looking infrared (FLIR) sensor mounted under the extended nose. The extended nose is built to facilitate installation of a weather radar to incorporated at a later date. A pod-mounted Multi-Mode Radar is located forward of the left main gear. A state-of-the-art avionics suite (GPS, INS, TACAN, ILS, VOR, ADF) is accessible through the Integrated Avionics Sub-system and is listed in Table A-1.

Table A-1 – IAS Avionics Systems

VHF AM/FM RADIO	TWO-WAY VHF COMMUNICATIONS
UHF-AM HAVE-QUICK RADIO	SECURE UHF COMMUNICATIONS
SATCOM UHF	SATELLITE UHF COMMUNICATIONS
VHF GROUND COMMUNICATIONS RADIO	VHF COMMUNICATIONS IN A FREQUENCY RANGE BEYOND NORMAL AIRCRAFT VHF FREQUENCIES
AIRBORNE TARGET HANDOVER SYSTEM	SECURE CAPABLE BURST TRANSMISSION TWO-WAY TARGET INFORMATION
VHF-FM SINCGARS	TWO-WAY SECURE VHF FREQUENCY HOPPING COMMUNICATIONS
HIGH FREQUENCY RADIO	LONG-RANGE SECURE HIGH FREQUENCY COMMUNICATIONS
VOICE SECURITY EQUIPMENT	ALLOWS CLEAR OR SECURE EMCRYPTMNET
VHF NAVIGATION AND ILS	PROVIDES VOR BEARING AND ILS LOCALIZER, GLIDE SLOPE AND MARKER BEACON
AUTOMATIC DIRECTION FINDER	PROVIDES DIRECTION FINDING AND HOMING
TACAN	PROVIDES BEARING AND/OR SLANT RANGE TO TACAN GROUND OR AIR STATION
PERSONNEL LOCATING SYSTEM	FACILITATES LOCATING DOWNED AIRCREW
GLOBAL POSITIONING SYSTEM	PROVIDES POSITION, VELOCITY, AND TIME INFORMATION TO IAS
INERTIAL NAVIGATION UNIT	PROVIDES LINEAR AND ANGULAR ACCELERATION, VELOCITY, POSITION, HEADING, ATTITUDE, BAROMETRIC ALTITUDE, BODY ANGULAR RATES AND TIME LAGS TO IAS
ATTITUDE HEADING REFERENCE	PROVIDES ACCURATE OUTPUTS OF PITCH, ROLL, HEADING ACCELERATION, VELOCITY, & POSITION TO IAS
DOPPLER NAVIGATION SYSTEM	PROVIDES VELOCITY INFORMATION TO IAS
AIR DATA COMPUTER	PROVIDES TRUE AIRSPEED, PRESSURE ALTITUDE, OUTSIDE AIR TEMPERATURE AND INDICATED AIRSPEED TO IAS
RADAR ALTIMETER	PROVIDES ABSOLUTE ALTITUDE ABOVE TERRAIN
IDENTIFICATION FRIEND OR FOE TRANSPONDER	RADAR IDENTIFICATION AND TRACKING
RADAR BEACON TRANSPONDER	RADAR IDENTIFICATION & TRACKING FOR IN-FLIGHT REFUELING OPERATION

APPENDX B

HUMAN RELIABILITY ANALYSIS

CAUSES OF HUMAN MALFUNCTION

- EXTERNAL EVENTS (DISTRACTIONS, ETC)
- EXCESSIVE TASK DEMAND (FORCE, TIME, KNOWLEDGE, ETC)
- OPERATOR INCAPACITATED (SICKNESS)
- INTRINSIC HUMAN VARIABILITY

FACTORS AFFECTING PERFORMANCE

- SUBJECTIVE GOALS AND INTENTIONS
- MENTAL LOAD
- RESOURCES
- AFFECTIVE FACTORS

SITUATION FACTORS

- TASK CHARACTERISTICS
- PHYSICAL ENVIRONMENT
- WORK TIME CHARACTERISTICS

MECHANISMS OF HUMAN MALFUNCTION

- DISCRIMINATION
 - STEREOTYPE FIXATION
 - SIMILAR SHORT-CUT
 - STEREOTYPE TAKEOVER
 - FAMILIAR PATTERN NOT RECOGNIZED
- INPUT INFORMATION PROCESSING
 - INFORMATION NOT RECEIVED
 - MISINTERPRETATION
 - ASSUMPTION
- RECALL
 - FORGET ISOLATED ACT
 - MISTAKE ALTERNATIVES
 - OTHER SLIP OF MEMORY INFERENCE
 - CONDITION OR SIDE EFFECT NOT CONSIDERED
- PHYSICAL COORDINATION
 - MOTOR VARIABILITY
 - SPATIAL MISORIENTATION

PERSONNEL TASK

- EQUIPMENT DESIGN
- PROCEDURE DESIGN
- FABRICATION
- INSTALLATION
- INSPECTION
- OPERATION
- TEST AND CALIBRATION
- MAINTENANCE, REPAIR
- LOGISTICS
- ADMINISTRATION
- MANAGEMENT

INTERNAL HUMAN MALFUNCTION

DETECTION

IDENTIFICATION

DECISION

SELECT GOAL

SELECT TARGET

SELECT TASK

ACTION

OPERATIONAL SEQUENCE

EXECUTION

COMMUNICATION

EXTERNAL MODE OF MALFUNCTION

SPECIFIED TASK NOT PERFORMED

OMISSION OF ACT

INACCURATE PERFORMANCE

WRONG TIMING

COMMISSION OF ERRONEOUS ACT

COMMISSION OF EXTRANEIOUS ACT

SNEAK PATH

ACCIDENTAL TIMING OF SEVERAL EVENTS OR FAULTS

APPENDIX C

MILITARY STANDARDS, MILITARY SPECIFICATIONS, & NASA TECHNICAL NOTES

MIL-STD-250D	Aircrew Station Controls and Displays for Rotary Wing Aircraft,	30 Sep 88
MIL-STD-411E	Aircrew Station Alerting Systems	30 Jun 70
MIL-STD-783D	Legends For Use in Aircrew Stations and On Airborne Equipment	30 Mar 79
MIL-STD-884C	Electronically or Optically Generated Displays for Aircraft Control and Combat Cue Information	4 Jan 72
MIL-STD-1295A	Human Factors Engineering Design Criteria for Helicopter Cockpit Electro-Optical Display Symbology	3 Aug 81
MIL-STD-1472D	Human Engineering Design Criteria For Military Systems, Equipment, and Facilities	2 May 81
MIL-STD-1478	Task Performance Analysis	13 May 91
MIL-SPEC-18012B	Marking For Aircrew Displays, Design and Configuration of	15 Mar 89
MIL-STD-46855	Human Engineering Requirements for Military System, Equipment, and Facilities	26 May 94
MIL-SPEC-85762 A	Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible	26 Aug 88
NASA-TM-86659	The Introduction of New Cockpit Technology: A Human Factors Study	May 85
NASA-TM-X3457	Rationale and Description of a Coordinated Cockpit Display For Aircraft Flight Management	Nov 76
NASA-TM-78559	An Advanced Cockpit Instrumentation System: The Coordinated Cockpit Display	1979
NASA-CR-177333	Human Factors of Cockpit Automation: A Field Study of Flight Crew Transition	Jul 85

APPENDIX D

GLOSSARY

AHRS	Attitude Heading Reference System
ATHS	Airborne Target Handover System
CAS	Calibrated Airspeed
CDU	Control Display Unit
CMS	Cockpit Management System
EFIS	Electronic Flight Instrument System
EMCON	Emissions Control
ENAV	Electronic Navigation
FLIR	Forward Looking Infrared
HRA	Human Reliability Analysis
HSD	Horizontal Situation Display
IAS	Integrated Avionics Subsystem
ICS	Intercommunication System
IFF	Identification Friend or Foe
MFD	Multi-Function Display
NAV	Navigation
NRP	Navigation Reference Point
NVG	Night Vision Goggles
RALT DCPLD	Radar Altimeter Decoupled
SOA	Special Operations Aircraft
SOCOM	Special Operations Command
SOF	Special Operations Forces
TNAV	Tactical Navigation
VSD	Vertical Situation Display
VWS	Vice Warning System
WCA	Warning, Caution and Advisory system

VITA

David Allan Downey was born in San Francisco, California on September 1, 1955. He attended various schools in Virginia, California, Kansas, Germany and graduated from James W. Robinson Jr. Secondary School (Fairfax, VA) in June 1973. He has a Bachelor of Science degree in Aviation Technology from Embry Riddle Aeronautical University, Daytona Beach, Florida. He is a graduate of the U.S. Navy Test Pilot School, Patuxent River Naval Air Station, Maryland and the U.S. Army Command and General Staff College, Ft. Leavenworth, Kansas. In January 1994, he entered the University of Tennessee Space Institute, Tullahoma and in August 1995 received a Master of Science degree in Aviation Management.

He is a retired U.S. Army officer and is currently employed by the Federal Aviation Administration as a Flight Test Pilot.