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# Applying Human Factors Principles In Aviation Displays: A Transition From Analog to Digital Cockpit Displays In The CP140 Aurora Aircraft

Ryan C. Palmer

*University of Tennessee - Knoxville*

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To the Graduate Council:

I am submitting herewith a thesis written by Ryan C. Palmer entitled "Applying Human Factors Principles In Aviation Displays: A Transition From Analog to Digital Cockpit Displays In The CP140 Aurora Aircraft." 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.

Rich Ranaudo, Major Professor

We have read this thesis and recommend its acceptance:

Stephen Corda, Peter Solies

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

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

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Dr. Stephen Corda

Dr. Peter Solies

Accepted for the Council:

Dr. Carolyn R. Hodges,  
Vice Provost and Dean of  
The Graduate School

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

**IMPLICATIONS OF VIOLATING HUMAN FACTORS  
DESIGN PRINCIPLES IN AVIATION DISPLAYS:  
*AN ANALYSIS OF FOUR MAJOR DEFICIENCIES IDENTIFIED DURING THE  
TEST AND EVALUATION OF A COCKPIT MODERNIZATION PROGRAM ON  
THE CP140 AURORA AIRCRAFT***

A Thesis  
Presented for the  
Master of Science in Aviation Systems  
Degree  
The University of Tennessee Space Institute, Tullahoma

Major Ryan C. Palmer  
August 2007

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*The opinions expressed in this document are those of the author and are not necessarily those of the Department of National Defence, the Canadian Forces, or CMC Electronics Inc.*

## Acknowledgements

First, I would like to express my gratitude to the Canadian Forces for providing me with the many years of training, education and experience that underpin this work, and I wish to dedicate this paper to my colleagues, the men and women of the Canadian Forces who work tirelessly in the quest for justice and freedom, sometimes sacrificing their lives in the pursuit of these ideals.

I would also like to convey my sincere appreciation to Major Mike Barker who spent countless hours reviewing this document for both content and technical accuracy and offered invaluable advice through each stage of its development.

While I am grateful to everyone involved in the NFIMP test program, I wish to single out one individual for his extraordinary dedication, work ethic and contributions to the NFIMP program and to this paper. Mr. Jim Hastie has been a true inspiration, and I am indebted to him for his support, his willingness to listen and his heart-felt desire to create the best possible product for the Canadian Forces.

Most importantly, I would like to thank my wife who kept me sane and balanced throughout this project. She was my chief editor and my sounding board and spent many hours reviewing this document and providing her professional advice. The success of this project would not have been possible without her support and I am forever grateful to her for her love, encouragement and most significantly, her patience.

## Abstract

A flight test program that evaluated the results of a CP140 Aurora cockpit modernization project was conducted between May 2004 and October 2005. This paper uses the results of that test program to show how basic human factors principles were violated which led to the identification of multiple design deficiencies. This paper proposes that the failure to apply good human factors principles when designing aircraft displays can lead to unacceptable deficiencies. The result can be poor modal awareness, confusion in the cockpit, and often negative training for the pilots. In particular, four major deficiencies were analyzed to determine the specific human factors principles that were breached. The violations included a lack of concise and relevant feedback to the pilot, unclear and ambiguous annunciations, poor use of colour coding principles and logic, a lack of suitable attention capture cueing, inappropriate alert cueing, an absence of aural cueing during specific degraded modes of operation, excessive cognitive workload, and a failure to incorporate the pilot as the focal point of the display design, also known as a human centred design philosophy. Recommendations for system design enhancements are provided to ensure safe and effective operations of this prototype system prior to operational implementation.

The evaluation of the prototype system design was conducted by a flight test team from the Aerospace Engineering Test Establishment in Cold Lake, Alberta and supported by the Maritime Proving and Evaluation Unit in Greenwood, Nova Scotia. The test program encompassed a thorough review of system design documentation, abinitio training and preliminary testing in a Systems Integration Lab and 40 flight test missions. The recorded deficiencies were based upon the observations of two Qualified Test Pilots.



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## Glossary of Terms

<b>ACs</b>	Advisory Circulars
<b>ACP</b>	AFDS Control Panel
<b>AESOP</b>	Airborne Electronic Sensor Operator
<b>AETE</b>	Aerospace Engineering Test Establishment
<b>AFCS</b>	Automatic Flight Control System
<b>AFDS</b>	Autopilot and Flight Director System
<b>AIMP</b>	Aurora Incremental Modernization Project
<b>AMS</b>	Avionics Management System
<b>AP</b>	Autopilot
<b>ARPs</b>	Aerospace Recommended Practices
<b>CARs</b>	Canadian Aviation Regulations
<b>CDU</b>	Control Display Unit
<b>CF</b>	Canadian Forces
<b>DCP</b>	Display Control Panel
<b>DND</b>	Department of National Defence
<b>DOD</b>	Department of Defence
<b>DTA</b>	Directorate of Technical Airworthiness
<b>EFDI</b>	Electronic Flight Director Indicator
<b>EFDS</b>	Electronic Flight Display System
<b>EGI</b>	Embedded GPS and INS
<b>EHSI</b>	Electronic Horizontal Situation Indicator
<b>FAA</b>	Federal Aviation Administration

<b>FARs</b>	Federal Aviation Regulations
<b>FD</b>	Flight Director
<b>FDI</b>	Flight Director Indicator
<b>FOV</b>	Field of view
<b>GPS</b>	Global Positioning System
<b>HF</b>	Human Factors
<b>HFACS</b>	Human Factor Analysis and Classification System
<b>HFE</b>	Human Factors Engineering
<b>HSI</b>	Horizontal Situation Indicator
<b>IFF</b>	Identification Friend or Foe
<b>ILS</b>	Instrument Landing System
<b>INS</b>	Inertial Navigation System
<b>ISR</b>	Intelligence, surveillance and reconnaissance
<b>L-H</b>	Liveware-Hardware
<b>L-S</b>	Liveware-Software
<b>MIL STDs</b>	Military Standards
<b>MP&amp;EU</b>	Maritime Proving and Evaluation Unit
<b>NFIMP</b>	Navigation and Flight Instruments Modernization Project
<b>OMI</b>	Operator-machine interface
<b>PFR</b>	Post Flight Report
<b>PR</b>	Problem Reports
<b>QTP</b>	Qualified Test Pilot
<b>RAAWS</b>	Radar Altimeter and Altitude Warning System

<b>RADALT</b>	Radar Altimeter
<b>SAE</b>	Society of Automotive Engineers
<b>SAR</b>	Search and Rescue
<b>SIL</b>	System Integration Lab
<b>SOP</b>	Standard Operating Procedures
<b>SUT</b>	Systems under test
<b>TACAN</b>	Tactical Air Navigation System
<b>TCAS</b>	Traffic Collision and Avoidance System
<b>VHF</b>	Very High Frequency
<b>VOR</b>	VHF omni-directional range

## Chapter 1 - Introduction

The Aerospace Engineering Test Establishment (AETE), a sub-unit of the Canadian Forces Flight Test Center, conducted a flight test program to evaluate the results of a CP140 Aurora cockpit upgrade between May 2004 and October 2005. AETE, a lodger unit of 4 Wing, located in Cold Lake, Alberta, is the primary developmental flight test agency in the Canadian Forces (CF). AETE was augmented throughout this program by members of the Maritime Proving and Evaluation Unit (MP&EU) located at 14 Wing in Greenwood, Nova Scotia. MP&EU is the CF's operational flight test unit for the CP140 fleet. Numerous deficiencies, many of which were considered unacceptable in whole or in part due to human factors considerations, were uncovered by the combined test team through the testing and evaluation of the new systems and displays.

This paper proposes that the failure to apply good human factors principles when designing aircraft displays can lead to unacceptable deficiencies. The violation of sound human factors principles can result in poor modal awareness, confusion in the cockpit and, in many cases, negative training for the pilots. This can produce less effective and less efficient systems, increase the frequency of pilot error and can sometimes compromise the flight safety of the aircraft. Specifically during the test and evaluation of the CP140 Navigation and Flight Instruments Modernization Project (NFIMP), an analysis of four major deficiencies highlighted the following human factors design principle violations: a lack of concise and relevant feedback to the pilot; unclear and ambiguous annunciations; poor use of colour coding principles and logic; a lack of suitable attention capture cueing; inappropriate alert cueing; an absence of aural cueing during specific degraded modes of operation; excessive cognitive workload; and a failure



to incorporate the pilot as the focal point of the display design, also known as a human centred design philosophy. Recommendations for system design enhancements are provided to ensure safe and effective operations of this prototype system prior to operational implementation.

### *Background*

The Canadian government purchased the CP140 Aurora, a large four engine turboprop aircraft designated as a long range patrol aircraft, in the early 1980s to serve as the primary CF maritime patrol aircraft. The CP140 is a multi-role platform responsible for a wide array of missions that range from anti-submarine warfare to intelligence, surveillance and reconnaissance (ISR) to search and rescue (SAR) to special operations (Department of National Defence [DND], 2001). Several photographs showcasing the CP140 aircraft in its operational environment can be seen in figures 1.1, 1.2 and 1.3.

The age of the Aurora aircraft led the Department of National Defence (DND) to establish the Aurora Incremental Modernization Project (AIMP) as a way to upgrade flight and mission essential systems that were becoming obsolete. One element of the AIMP was the Navigation and Flight Instruments Modernization Project (NFIMP), which consisted of an Avionics Management System (AMS), an Electronic Flight Display System (EFDS), an Automatic Flight Control System (AFCS), a Radar Altimeter and Altitude Warning System (RAAWS), a Traffic Collision and Avoidance System (TCAS) and a new Identification Friend or Foe (IFF) system. The deficiencies that were discovered during the testing and evaluation of these systems led to the initiation of this paper and serve as its foundation.



*Figure 1.1.* The CP140 returning from a fisheries patrol.



*Figure 1.2.* The CP140 conducting a low-level, over-water ASW mission.



*Figure 1.3.* The CP140 involved in a SAR mission over the Rocky Mountains.

### *Description of the Deficiencies*

The systems under test were evaluated first through a review of the system design documentation, followed by a series of familiarization sessions in the contractor's System Integration Lab (SIL) and finally through a series of flight tests. The test team highlighted many potential deficiencies during the document review and familiarization stages of the test program, however it was not until the flight test stage that the systems could be fully evaluated by the test pilots in an operational environment.

Upon completion of the initial NFIMP test program in October 2005, over 1100 flight related deficiencies had been identified. Four of these deficiencies have been selected for discussion in this paper due to their impact on the successful accomplishment of the mission, their impact on pilot workload as well as their potential effects on flight safety. The four deficiencies are outlined in the following four paragraphs.

#### *Deficiency One – Autopilot and Flight Director System (AFDS) Loss of Signal*

The first deficiency involved poor pilot feedback from the AFDS/EFDS operator-machine interface during the loss of a selected navigation source. The resultant loss of situational awareness and delayed response time resulted in aircraft excursions from the desired track. This also increased pilot workload and created an appropriate backdrop for an in-flight incident or accident.

#### *Deficiency Two – Automatic Flight Control System (AFCS) Disengagement Feedback*

The second deficiency was a failure of the electronic flight displays to provide clear and unambiguous feedback to the pilot after any disengagement of the AFCS, or

autopilot. There were two types of disengagements: normal and non-normal, and there were deficiencies associated with both. A non-normal disengagement was any disengagement that occurred and was not initiated by the pilot through the primary method of disengagement. This deficiency was observed any time the autopilot became disengaged. The lack of a clear, easy to understand signal to the pilot indicating the appropriate autopilot disengagement mode resulted in an increase in cognitive processing time and a decrease in pilot response time. If left uncorrected, this would create confusion in the cockpit and under certain conditions could be catastrophic. One such situation occurred on December 29, 1972 when a L1011 Tristar aircraft crashed into the Florida everglades after the pilot inadvertently disconnected the autopilot while the crew was troubleshooting a malfunctioning landing gear indicator. No one realized that the autopilot had become disconnected and the aircraft descended into the everglades, killing 101 of 176 people onboard (NTSB, 1972).

### *Deficiency Three – Unselected Approach Guidance*

The third deficiency was misleading approach guidance that was displayed on the EFDS for approaches that were not selected by the pilot. A standard display design would require the pilot to physically select the desired navigation source, in addition to having a valid and tuned frequency or channel in the navigation control set. In the NFIMP system, regardless of what navigational guidance was chosen for display on the EFDS, the ILS or localizer approach symbology would automatically appear on the EFDS whenever a valid frequency was dialed into the ILS receiver. This was first observed while flying a non-precision military TACAN instrument approach and precision ILS approach guidance

was also being displayed on the EFDS. This was confusing to the pilot and required extra time to process what information was relevant and what information was not. This design would have the undesired effect of conditioning the aircrew to selectively disregard information provided to them on their primary flight displays and for miscommunication and confusion in the cockpit during a critical phase of flight.

*Deficiency Four – Coupled versus Uncoupled status of the Autopilot and Flight Director System (AFDS)*

The fourth deficiency was an inconsistent method of displaying the coupled state of the autopilot on the EFDS. When the autopilot was engaged, it was either coupled or uncoupled. This was an important distinction and it was important for the pilot to easily ascertain the correct state of the autopilot. The prototype design used two different methods of displaying this information, which led to confusion in the cockpit. This deficiency was first observed when the aircraft deviated from the desired flight path because the test pilot had mistakenly believed the autopilot to be in a coupled state. A failure to address this deficiency would result in a reduction in situational awareness, extra cognitive processing time for the pilots, and an increase in workload. Further, this deficiency could cause a deviation from the desired flight path, which could be catastrophic under certain conditions.

*Significance*

In the early days of aviation accident investigation, errors and causal factors were often attributed directly to the pilot. Historically, well over half of all aircraft accidents were attributed to human causal factors. For air carriers, approximately two-thirds of all

accidents are attributable to the cockpit crew while in general aviation, human causes are responsible for almost nine out of ten accidents (Nagel, 1988, p. 266).

A systems approach to accident investigation has become widely accepted within the military and civilian flight safety communities. Using a systems approach, we look at errors and causal factors that can also be attributed to the systems themselves. Human Factors Engineering (HFE) is often applied to designs in an attempt to minimize error by making the systems more forgiving or error tolerant.

In all of the deficiencies listed above, insufficient, unclear or misleading information is provided to the pilot. A failure to provide the pilot with the accurate and necessary information in a timely manner can lead to errors in judgment and poor decisions that can in turn compromise flight safety and mission effectiveness. While human error may remain a primary cause factor in the majority of accident investigations, improving system design and the implementation of procedures can assist the pilot and reduce the potential for such errors to occur. This paper uses a systems approach to address the potential for human error. Through analysis of the four deficiencies listed above, this paper makes recommendations for system enhancements to reduce the likelihood that these errors will occur.

## Chapter 2 – Literature Review

Transforming an antiquated cockpit with analog displays to a modern glass cockpit is a challenging task. It is particularly challenging when conducting a partial upgrade program where only part of the cockpit is undergoing the modernization. This is due to the fact that it is often easier to re-design the complete network of interrelated systems using a common philosophy than to try to integrate individual segments on a piece-by-piece basis. Notwithstanding the challenges of integrating all of the individual sub-components, there are basic human factors principles that must be considered in the design of each new piece of equipment such that it contributes in a positive way to the overall efficiency, effectiveness and safety of the flight operations. One of the goals of modern, high technology glass cockpits is to improve safety and efficiency by reducing pilot workload and eliminating the human errors that have contributed to past aviation accidents. While advances in automation have been shown to reduce certain areas of workload and certain types of errors, automation has also been shown to cause an increase in workload in other areas and has spawned new sources of potential error (Sarter & Woods, 1995; Woods, 1993; Masalonis et al., 1999). This chapter provides an overview of current literature in the areas of human factors, human error, display design considerations (such as colour coding, auditory cueing, display clutter and cognition), and the topical issue of modal awareness as they relate to the deficiencies outlined in this paper.

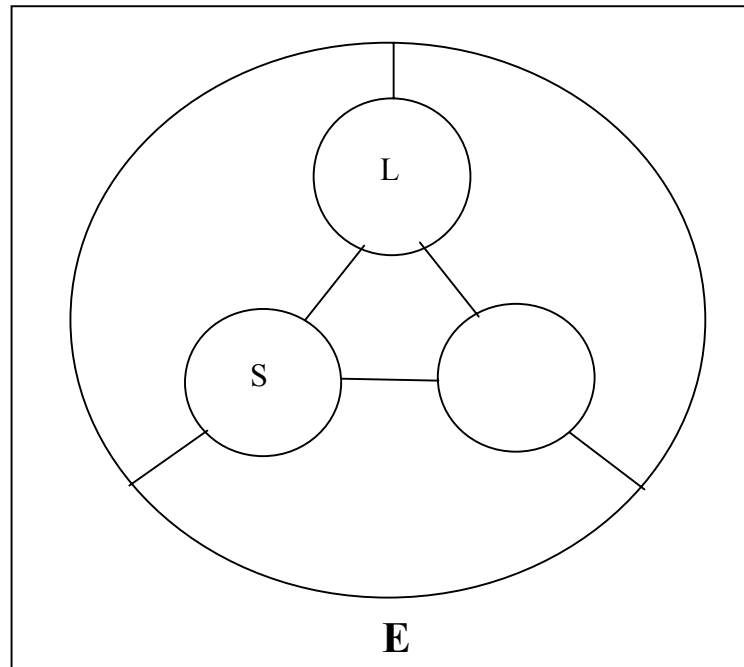
### *Human Factors*

In an attempt to determine an appropriate and useful definition for human factors, Licht & Pozella (1989) discovered that collectively, more than 90 definitions exist to



explain the terms human factors, ergonomics and human factors engineering. Despite ongoing discussions regarding the “sharp distinctions” (Licht et al., 1989, p. 5) amongst these terms, others such as Elwyn Edwards (1988) argue that for most situations, these terms may be considered to be synonymous. Therefore, for the purpose of this paper, the terms human factors, ergonomics and human factors engineering will be used interchangeably. The following definition, taken from J. Adams (1989) book on Human Factors Engineering, provides a broad definition from which we can work: “The field of human factors engineering uses scientific knowledge about human behavior in specifying the design and use of a human-machine system. The aim is to improve system efficiency by minimizing human error” (p. 3).

In 1972, Edwards published a conceptual model that is a useful tool in understanding the practical application of human factors’ principles. Edwards’ SHELL model (Figure 2.1) describes the interactions between software, hardware, and liveware, as well as the environment in which they all coexist. Software is identified as the rules, regulations, standard operating procedures, customs, practices and habits that guide the operation of the system and the way the human operator is expected to interact with it. The hardware comprises the physical components of a system, the displays, antennae, control panels, and may also include the building, aircraft, or any other physical material. Liveware is the term used to describe the human component, that which operates the system. The environment is the overall context in which the interactions take place, and may include such things as economic, political and social factors. Using this construct, it becomes easier to visualize and understand the interactions that represent the primary concern of the field of Human Factors Engineering.



*Figure 2.1.* SHEL Model.

The SHEL model showing the relationships between the liveware (humans), the software (rules, regulations, standard operating procedures), hardware (panels, displays, levers) and the environment in which they all coexist. Human Factors is interested in optimizing the interaction of these components.

This paper focuses primarily on the interfaces of the interactions between components within the physical construct of a cockpit. “It is certainly true that mismatches at the interfaces, rather than catastrophic failures of single components, typify aviation disasters” (Edwards, 1988). The interface between the liveware and hardware, or L-H interface, is often referred to as the operator-machine interface and is one of the primary areas of discussion in this paper. The interface between the liveware

and software, or L-S interface, will also be addressed through discussions concerning the resolutions of deficiencies identified in the L-H interfaces.

### *Flight Safety and Human Error*

The aviation industry has a high level of interest in human factors, ergonomics and human factors engineering due to its impact on three areas: safety, efficiency of the system and the well-being of crew members (Civil Aviation Authority, 2002). In terms of flight safety, results of an analysis of accident data by Alan Hobbs (2004) suggest that human factors have been the primary flight safety issues since the early days of aviation. It was a desire to maximize flight safety and to strive for the optimal operational efficiency of the NFIMP prototype systems that led to the identification of the deficiencies listed in this report.

Safety is among the highest priorities of any aviation organization whether it be general aviation, commercial aviation or the military (during peacetime operations). Flight safety and human error are undeniably linked. Human error has been recognized as the primary or secondary cause factor in as many as 87% of accidents (Allnut, 2002; Javaux, 2002; Amalberti & Wioland, 1997; Nagel, 1988). However, stating that human error is a causal factor in a majority of accidents is only a first step towards improving the flight safety of aviation systems.

Human error can itself be a nebulous term. Similar to the ambiguities that exist for the definition of human factors, there are also an abundance of differing opinions on human error, what constitutes an error, how human errors are measured, and so on (Wiegmann & Shappell, 2000; Nagel, 1988). Historically, accident investigations have labelled human error (or pilot error for our purposes) as a primary cause of an accident

without further explanation. What researchers have discovered is that the analysis must probe deeper if there are to be realized gains toward flight safety. To this end, there are two general approaches to using an analysis of human error to improve safety. One school of thought is that ‘to err is human,’ a thought process that suggests humans will make mistakes regardless of whatever preventative efforts are made. This philosophy proposes that the best approach is therefore not to attempt to prevent error, but to design error tolerant systems (Amalberti & Wioland, 1997). That is to say, systems designed not only to recognize the onset of an error, but also to be a fully reversible system to permit the operators to correct their errors such that any errors made would not result in catastrophic accidents. The second approach argues “there is no empirical data to support the premise that to err is an inherent human trait” (Bogner, 2002, p. 111). This approach is based on the belief that human error is preventable and the objective should be to design systems and create procedures or methodologies with the goal of reducing or eliminating human error. The best solution is probably one that subscribes to both philosophies, attempting to minimize errors whenever possible and simultaneously, to create more error tolerant systems.

In circumstances when the pilot has committed the final unsafe act that resulted in the accident or incident, it is easy to focus on the pilot as the primary causal factor in the subsequent accident investigation. The literature shows, however, that this is a shortsighted perspective and overlooks possible underlying issues or factors that may have led to the error. To this end, Reason (1990) proposed a unique and appealing approach to looking at human error that has gained widespread acceptance in the aviation community. Wiegmann & Shappell (2001) built upon Reason’s work to create the

Human Factor Analysis and Classification System (HFACS) as a method to analyze human error in aviation accident investigations. The HFACS is currently being used within both the U.S. and Canadian military Aviation Safety Directorates. Reason argues that in addition to the active failures leading to an unsafe act, there are latent failures as well. These latent failures can exist but lay dormant for days, weeks, months or years, and can range from problems within an organizational culture to inappropriate supervision, or in the case of the deficiencies listed in this paper, design flaws. The HFACS model proposes that the potential for accidents exists when the latent and active failures are aligned. Reason argues that our success in preventing accidents lies in our ability to break any link in the chain of events that led to the accident.

#### *Display Design*

The topic of display design and the ramifications of a seemingly small design flaw are of great importance for this paper. The design of a display is an incredibly complex task and the application of HFE in the design is essential. To assist in this process there is an abundance of guidance documentation that exists in the form of U.S. Department of Defence (DOD) Military Standards (MIL STDs), U.S. DOD military handbooks, Federal Aviation Regulations (FARs), Canadian Aviation Regulations (CARs), FAA Advisory Circulars (ACs), Society of Automotive Engineer (SAE) reports and Aerospace Recommended Practices (ARPs). The primary documents used in the analysis of the design deficiencies discussed in this paper were MIL-STD-1472F on Human Engineering (1999), MIL-STD-411F on Aircrew Station Alerting Systems (1997), FAA-AC-25-11 on Transport Category Airplane Electronic Display Systems (1987), SAE/ARP 1874 on Design Objectives for CRT displays for Part 25 Aircraft

(1988), SAE/ARP 4102 on Flight Deck Panels, Controls and Displays (1988), and SAE/ARP 4102/7 on Electronic Displays (1988). These guidance documents provide standardization and direction to enhance the safety and usability of systems based upon years of experience and lessons learned through research and accident investigations. These reference documents provide the designers with vast amounts of information ranging from appropriate font sizes to standard colour coding to display layout, and include guidance on most aspects of design consideration, including human cognition.

Of paramount importance when considering the design of aviation displays is the role of the pilot, which Billings championed in his 1991 paper entitled ‘Human Centered Aircraft Automation Philosophy.’ A technology-centered automation approach is the opposing design philosophy to the human-centered automation approach that Sarter & Woods (1995) argue is at the heart of many human factors issues and modal awareness problems. Palmer, Rogers, Press, Latorella and Abott (1995) also support crew-centered flight deck design philosophy and back it up with numerous references and significant research. A technology-centered approach may contain the most advanced methodologies and capabilities but the complexities of such a design philosophy may make the system difficult to use and may lend itself to confusion and errors by the operators. A human-centered approach takes into account the limitations of the operator but also considers the operator’s strengths to achieve an optimum design that supports and assists the operator instead of causing confusion. Palmer et al. (1995) best summarize the current philosophy on flight deck design in the following way: “Supporting the pilot as an individual operator is the primary focus of most current human factors guidance – [the] design must account for all that is known about how humans perform tasks” (p. 13).

Within the context of a human-centered design philosophy, the deficiencies in this paper highlight issues involving standard colour coding principles, the use of different types of cuing to enhance situational awareness and response time, the inclusion of ambiguous information or lack of salient system details, display clutter and the critical aspect of human cognition as it relates to display design.

### *Colour Coding Principles*

“There are a number of cognitive factors that must be considered if colour is to be used in visual displays” (Dry, Lee, Vickers & Huf, 2005, p. 13). The use of colour in aviation displays can either assist or hinder the pilot depending on how it is applied. The use of too many colours or the use of colours to link non-standard associations (e.g. using brown instead of blue for the sky) can result in increased processing time and may lead to confusion and incorrect responses. When used appropriately, colours can assist to distinguish separate but closely grouped items and connect special meaning to words. For example, GAMA publication No. 12 (2004) which is one of the FAA’s accepted recommended practices and guidelines for an integrated cockpit states that “coupled flight guidance modes should be green, warnings should be red, and cautions or abnormal states should be yellow or amber” (p. 22). Other publications indicate that colours should be linked with abstract concepts such as red’s association with danger, yellow with caution and green with safety (Dry et al., 2005). These are the same accepted standards that are integrated into people’s everyday lives and are engrained in our thought processes. Traffic lights are an excellent example of this.

The U.S. Department of Defence military standards specify colour-coding schemes for use in visual displays (Helander, 1987) and these same standards are in use within the Canadian military. Nikolic, Orr and Sarter (2001) argue that “expectations of a particular type of signal, such as onsets or colour change, will increase the likelihood of that particular cue to capture attention” (p. 5A3-1). The strategic use of colour in aviation displays can provide a notable contribution to the efficiency and safety of the display design.

With today’s highly complex and information laden systems, it is increasingly important to direct, or cue, the pilot to look to the right place at the right time to receive the right pieces of information. One way to attract the pilot’s attention is through the use of changing colour, as was discussed above. Visual displays also frequently use the onset or flashing of a display element to cue the operator to a significant event. Current literature indicates that this latter method of grabbing the pilot’s attention may not be effective. “Recent research findings and operational experiences in data-rich event driven domains, such as aviation, suggest that this design approach which was supported by findings from early basic research on attention capture is not always successful” (Nikolic et al., 2004, p. 39). According to Nikolic et al. (2004) the early research was basic in nature using simple displays and simple tasks that are not representative of the more complex and real-world environment of today’s aviation displays. The argument is that if a person is focused and their attention is locked then a flashing event alone may be insufficient to capture the individual’s attention.



### *Auditory Cuing*

One technique that is useful in grabbing the pilot's attention is the use of auditory systems. One of the advantages of an auditory system is that it is not limited to the pilot's visual field of view (FOV) but essentially has an unlimited FOV because it can achieve attention getting results regardless of where the pilot may be looking (Flanagan, McAnally, Martin, Meehan & Oldfield, 1988). One has to be cautious about using auditory systems, however, as there can also be pitfalls to these types of systems such as using similar sounds for different alert states or long auditory phrases (Wickens & Flach, 1988).

Auditory systems are not suitable as an all encompassing cuing system. Over-use of auditory signals can confuse a pilot and create errors. A very successful and common use of auditory cues can be found in warning systems. Research has shown that subjects can respond more quickly to auditory warning signals than to visual ones (Dry et al., 2005; Wicken & Flach, 1988). Further studies indicate that auditory cues can be particularly useful in visually demanding environments (Sorkin, 1987; Wickens et al., 1988). It is clear from this literature that just as colour has an important role in modern aviation displays, the appropriate implementation of auditory systems can be an enhancing feature to increase the likelihood of acknowledging a time critical cue, thus enhancing efficiency and safety.

The placement of the cue in the display or the location of the cue in the cockpit is also an important factor. If an attention getting cue is located in the pilot's primary FOV it is more likely he will notice it. If the pilot has to look outside his FOV within the cockpit to perceive an alert, it is more likely that he will miss it (Flanagan et al, 1988).

This is a primary reason for annunciator panels and flashing master caution and master warning lights (located in a pilot's primary field of view). In their paper on attention capture, Nikolic et al. (2004) discuss the significance of cue location. While cues can be perceived at a peripheral angle of up to 50 degrees, this visual angle has been shown to decrease as the demands of a task increase. Further, the probability of detecting a visual cue decreases as the visual angle from the pilot's primary field of view increases.

The final aspect of attention cuing that relates to this paper is the issue of cue or signal similarity. Palmer et al. (1995) argue that to reduce the chance of confusion, alerts should be clearly distinct. If the pilot is forced to search for secondary sources of information to corroborate the warning cue when the same cue is used for separate and unique alerting conditions, the result may be a time lag between the onset of the cue and a comprehension of what the cue means. This situation can lead to a loss of situational awareness, potentially at a critical moment in time. Palmer et al. (1995) conclude that "for distinction, different alerts with different intentions should sound and appear dissimilar" (p. 30).

### *Display Clutter*

Display clutter must also be considered in the design of a display. With the advent of electronic displays, it has become possible to overwhelm the pilot with an overload of information. If the designer provides the operator with too much information, the operator may be incapable of processing it all, especially during periods of high stress such as emergency situations.

There is sometimes a fine line between providing the pilot with too much information and not providing him with enough information, and the difference to the pilot can be significant. The challenge is to provide the right amount of information at the right moment to allow the pilot to make the right decision. It is essential that the designer achieve the correct balance between excessive display clutter, especially when some of the information is extraneous or irrelevant, and providing salient data, the evaluation of which is an important function of the flight test personnel. Display clutter is an issue that relates directly to fundamental human limitations (Palmer et al., 1995). Numerous researchers have studied the implications of display clutter and there is consistent agreement as to the problems it can cause (Civil Aviation Authority, 2002; Wickens & Carswell, 1995; Stokes et al., 1988).

One of the primary issues associated with display clutter is that of close spatial proximity. This makes it more difficult to discriminate between individual units of information and their source. It can also disrupt the ability of the operator to observe movement or change to the display indicators. Another primary issue is that of excess information, due to the cognitive limitations of the operator. An excess of information inhibits the operator's ability to process the information, resulting in a breakdown in decision-making ability and increased response time.

While display clutter can be a notable problem, an insufficient level of detail or the absence of salient cueing can be just as significant. Wickens et al. (1988) discuss the absence of cues when discussing issues related to perception. They refer to an analysis of an aircraft crash conducted by Fowler (1980) to elaborate the point. In the investigation it was noted that the absence of an 'R' on the pilot's airport chart was the only way to know

that the airport did not have radar. Since this information can be critical to the pilot, Fowler argues that it is better to call attention to the absence of this capability by the inclusion of a symbol. An 'R' with a line through it may have been a more obvious way of presenting this information to the pilot. "People simply do not easily notice the absence of things" (Wickens et al., 1988).

### *Cognition*

All of the preceding information deals with limitations in the human cognitive and information processing capability. Cognition relates to the perceiving or knowing of information and how we process information (Avis, W.S., 1989). Tied in with cognition are some of the fundamental human limitations such as memory, computation, attention, decision-making biases and task time-sharing. The issue of cognition in display design is not limited to the design of aviation displays. In their paper on submarine display design, Dry et al. (2005) discuss how human cognition influences the design of visual displays. They define cognition as "a broad term that is used to describe processes that are directly related to, or involved in, thinking, conceiving and reasoning" (p. 9). Without a human-centered design philosophy, or if the display design fails to account for human cognitive limitations, the result can be a system prone to errors, confusion and inherent inefficiencies.

With the advent of the modern glass cockpit and the increased complexity that comes with an increase in automation, it becomes increasingly important to understand how humans process information. One of the goals of automation in aviation is to assist pilots by reducing their workload. Often the task may become easier with automation but

mental workload can sometimes be higher due to the increased system monitoring that is required. As a result, not being hands-on often makes it more challenging for pilots to maintain situational awareness. Regardless of the purpose of the display, there is widespread agreement on the importance of considering cognition in display design and the need to account for the limitations in the way that humans process information (Wiegmann et al., 2000; Stokes et al., 1988; Woods & Sarter, 1998; Masalonis et al., 1999; Boy & Ferra, 2004; Allnutt, 2002).

#### *Modal Awareness*

The final topic that requires some discussion to complete a thorough literature review relevant to this paper is that of modal awareness. Modal awareness issues have become more prevalent with the development of advanced cockpits. As systems become more automated, pilots spend less time ‘hands on’ and more time as system monitors. In order to make sound decisions, the pilots need to maintain a high level of situational awareness, therefore timely and unambiguous feedback from the automated systems is of paramount importance. This is not always provided in current systems. According to Wiener (1989), the three most commonly asked questions on the highly automated flight deck are what is it doing, why is it doing that and what will it do next?

One of the potential ramifications of poor situational awareness with an automated system is the potential for automation surprises (Sarter, Woods & Billings, 1997). Automation surprises may be described as “situations where crews are surprised by actions taken (or not taken) by the autoflight system” (Woods et al., 1998, p. 5), and arise from an incorrect assessment or miscommunication between the automation and the operator. With automation surprises there is a disconnect between the operator’s

expectations of what should happen and what actually occurs. Woods et al. (1998)

suggest automation surprises occur due to the convergence of three factors:

1. automated systems act on their own without immediately preceding directions from their human partner;
2. gaps in user's mental models of how their machine partners work in different situations; and,
3. weak feedback about the activities and future behaviour of the agent relative to the state of the world (p. 6).

Other researchers, such as Endsley & Kiris (1995), view these automation surprises as a repercussion of the pilot being 'out of the loop.' They argue that passive processing results in a reduced level of situational awareness in automated conditions that diminishes the pilot's ability to detect errors and to manually intervene if, and when, required.

This lack of modal awareness and the onset of automation surprises, if recognized too late, can have dire consequences. On December 29, 1972, Eastern Airlines Flight 401 crashed a Lockheed L1011 into the Florida Everglades near Miami when the flight crew became distracted and did not notice that the autopilot had been inadvertently disconnected, killing 101 passengers and crew (NTSB, 1972). On January 20, 1992, an Air Inter crash near Strasbourg, France demonstrated why operating modes of an autopilot need to be unambiguously distinguishable as the Airbus A320 flight crew is believed to have mistakenly selected a 3,300 foot per minute vertical descent rate instead of a 3.3 degree descent angle. 87 people died in the Air Inter crash (NTSB, 1992). In 1995 a Boeing B-757 airliner crashed near Cali, Columbia, partially as a result of diminished situational awareness in their modern cockpit. 160 people perished in that accident (NTSB, 1995). A more comprehensive list of automation-related accidents can be found in Wiener and Curry (1980). The accidents highlighted above represent just a

few of the many examples that demonstrate how critical modal awareness is in the operation of automated cockpits.

Palmer et al. (1995) suggest ways in which systems may be better designed so as to avoid losses in situational awareness and to prevent automation surprises. They talk about actively informing the crew of what the automation is doing, both in terms of how and why. Emphasis is placed on the feedback of modal status to include human or automation initiated mode changes, and they go on to say that “the crew must be able to determine immediately whether a function is under automatic, semi-automatic or manual control, and if a function reverts from automatic to manual control, that reversion must be announced unambiguously to the crew to ensure they are aware of the reversion” (p. 26). In addition, to reduce the workload associated with the monitoring of automated systems, Palmer et al. (1995) suggest the automation should not be designed such that the pilot is required to continuously watch it over long periods of time. They go on to say that the automation status needs to be readily apparent to both pilots and that both pilots must be able to easily distinguish between normal and non-normal situations. These are all sound recommendations that bring the flight crew into the center of the design process.

### *Conclusion*

The information provided in this chapter serves as the foundation upon which subsequent arguments will be made, and should provide the reader with sufficient background to grasp the issues that are raised in the discussion of the four deficiencies. It is important for the reader to have a basic understanding of each of the topics presented above in order to make the link between aircraft accidents, incidents or system

inefficiencies, the human error that triggered them and the underlying causal factors that led to the human error in the first place.

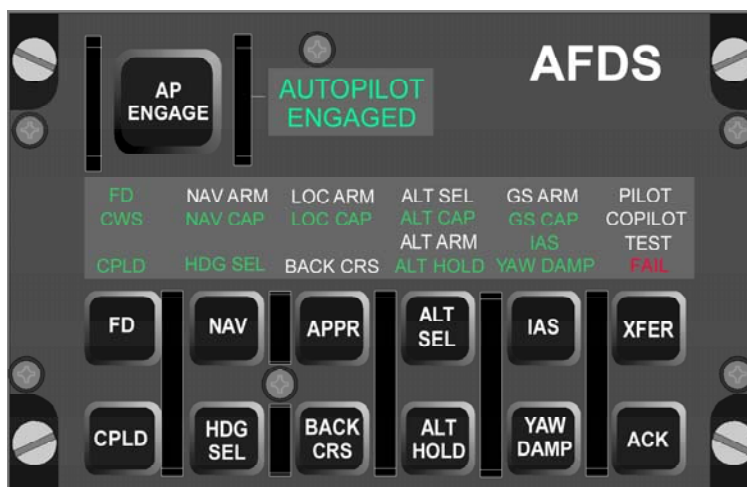


### Chapter 3 – Test Item Description

This chapter describes the basic operation of the systems discussed within this paper. The Navigation and Flight Instrument Modernization Project (NFIMP) system upgrade consisted of an Avionics Management System (AMS), an Electronic Flight Display System (EFDS), an Autopilot and Flight Director System (AFDS), a Radar Altimeter and Altitude Warning System (RAAWS), a Traffic Collision and Avoidance System (TCAS) and a new Identification Friend or Foe (IFF) system. The primary focus for discussion within this paper is the AFDS system. Since the AFDS system did not operate in isolation, but rather interacted and integrated with multiple other systems, a brief description of some of these other systems will assist the reader in following the arguments laid out in chapter 5.

#### *Autopilot and Flight Director System (AFDS)*

The AFDS was a digital replacement of the analog ASW-31 AFCS and flight director (FD) system that existed on the legacy CP140 aircraft. The AFDS combined both systems and was purchased as a functional replacement only. That is, the new system was designed to perform the same functions of the previous two systems with no additional enhancements. The main focus of the upgrade was to achieve an increase in reliability as the legacy systems were becoming obsolete; the components were breaking down more frequently and obtaining parts was becoming increasingly difficult. In addition to improved reliability, however, the new system also provided the user with significant increases in capability due to the advanced technology that was naturally embedded within the more modern unit. For example, the new system had the ability to fly fully coupled ILS approaches, an ability the old system lacked.



*Figure 3.1.* CP140 ACP showing the illumination of all possible mode selections.

Manipulation of the AFDS was through the AFDS control panel (ACP) as shown in Figure 3.1. The AFDS could be operated in a number of modes, categorized as either inner loop or outer loop modes. The inner loop modes were the basic stability modes of the autopilot and included attitude hold, heading hold and the yaw damper. The inner loop modes were not capable of affecting a change on the pitch or attitude of the aircraft, rather they simply maintained the attitude and heading as set by the pilot. All of the outer loop modes required one or more signals generated from outside the AFDS computer, such as the navigation mode or the approach mode. The AFDS could be operated as a stand-alone autopilot or flight director, or they could be engaged simultaneously. The autopilot (AP) portion of the AFDS could also be coupled or uncoupled. The term coupled meant that the AP was linked to the outer loop flight guidance. When the AP was engaged and coupled, it was directly connected to the aircraft control surfaces and was either actively manoeuvring the aircraft or was capable of manoeuvring the aircraft.

When the AP was engaged but uncoupled, it was working in its most basic state, capable of providing inner loop controls of attitude hold and heading hold only. The five possible control combinations for the AFDS are listed in Table 3.1.

The fourth combination shown in Table 3.1 had the highest potential for confusion. In this situation, the autopilot was engaged in the basic stability mode of attitude and heading hold and the flight director was providing steering guidance to a selected source (for example a TACAN station) in the form of flight director bars. In this example, the pilot would be required to manually fly the airplane (following FD guidance) as the autopilot would not be coupled to the flight guidance and therefore was incapable of manoeuvring the aircraft. In essence, the autopilot and FD were not linked. A depiction of the Electronic Flight Director Indicator (EFDI) communicating the AFDS status to the pilot is provided in Figure 3.2.

The AFDS could be disengaged in one of four ways: via the control wheel autopilot disconnect switch located on the outboard horn of the pilot or co-pilot control yokes; via the AP engage switch on the ACP; via the autopilot emergency disconnect; or due to any failure or reversionary mode. The only disengagement that was considered to be “normal” was a disengagement using the switches on the pilot or co-pilot control yokes. The other three methods of disengagement were considered “non-normal” disengagements and will be expounded upon in Chapter 5.

*Table 3.1. AFDS control combinations.*

This table shows the five control combinations and the functionality associated with each.

Combination #	FD	AP	Coupled	Capability
1		√		Basic AP stability mode. AP holds an attitude and heading as set by the pilot.
2		√	√	AP is flying the aircraft. It will follow whatever guidance is selected using the ACP and Display Control Panel (DCP).
3	√			FD provides flight guidance to the pilot for manual flying only. Guidance is governed by ACP and DCP selections.
4	√	√		FD provides flight guidance to the pilot for manual flying only. The autopilot can assist the pilot by maintaining an aircraft attitude and heading, as set by the pilot but AP cannot steer the airplane on its own.
5	√	√	√	The AP is flying the aircraft. It will follow whatever guidance is selected using the ACP and DCP. The FD shows the steering guidance that the AP is flying which can aid in situational awareness.



*Figure 3.2.* CP140 EFDI showing AFDS status combination 5 from Table 3.1.

In this screen capture the autopilot and FD are both engaged (green AP and FD annunciators in the top left hand corner of the display) and the AP is coupled to the flight guidance shown (green coupled bar). Two outer loop modes have been selected (TACAN navigation and altitude hold) and the FD is providing lateral and vertical guidance in the form of magenta flight director bars.

*Electronic Flight Display System (EFDS)*

The EFDS consisted of three main interfaces: the EFDI, the electronic horizontal situation indicator (EHSI) and the DCP. The EFDI and EHSI were digital replacements of the CP140's analog Flight Director Indicator (FDI) and Horizontal Situation Indicator (HSI) and the DCP replaced the legacy HSI control panel. While the EFDS was only intended to be a functional replacement of the legacy systems, the new "glass" displays provided a significant increase in capability. The software, design philosophy and human factors considerations were the only constraints that limited the amount of information that was displayed on the electronic displays. The EFDI, EHSI and DCP are shown in Figures 3.2, 3.3 and 3.4, respectively.

The EFDI was the most relevant display to the deficiencies discussed in this paper. The EFDI was the primary display to communicate the AFDS status and provide feedback to the pilot or co-pilot regarding mode transitions. This feedback and interaction was referred to as the human or operator machine interface and was critical for maintaining the situational awareness of the flight crew. The DCP was significant because of the way in which it controlled the information presented on the electronic flight displays. As well, it was selections on the DCP that determined what signals the autopilot would track in the approach and navigation sub-modes (DND, 2003a).



*Figure 3.3.* CP140 EHSI in the VOR navigation mode.

In this screen capture VOR1 is the selected source for lateral navigation and bearing pointers 1 and 2 are selected to VOR2 and VOR 1 respectively.

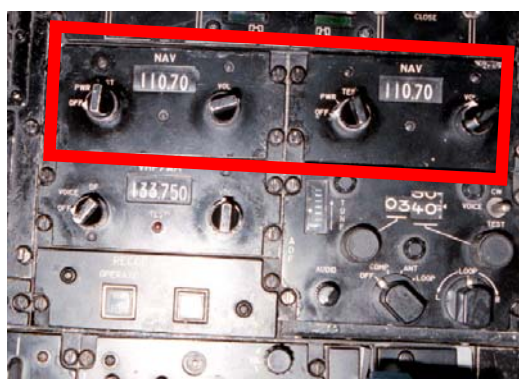


*Figure 3.4.* CP140 DCP.

This figure shows the arrangement of controls for selecting navigation sources and display information. The center knob controls the navigation source for the EHSI and also the AFDS. When engaged through the AFDS, guidance to the selected navigation source can be displayed on the EFDI.

### *Legacy Navigational Aids*

Some of the legacy navigational aids on the CP140 included the VOR, ILS and TACAN systems. The VOR and TACAN systems were both radio navigation systems that could be used for enroute navigation or non-precision instrument approaches. The ILS was a precision approach system that guided the pilot to the landing runway. The VOR and ILS systems shared the same control head. As a result, the VOR and ILS systems were not individually selected but were differentiated by virtue of the frequency set into the control head by the pilot. The TACAN was an independent system with its own transmitter, receiver and antenna. These legacy systems were fully integrated with the new digital NFIMP components allowing the AFDS to fully couple to any of these systems through selections on the Display Control Panel and the AFDS Control Panel. The two VOR/ILS control heads are shown in Figure 3.5 and the TACAN can be seen in Figure 3.6.



*Figure 3.5. CP140 VOR/ILS 1 and VOR/ILS 2*

These two receivers are independent but redundant systems. This control set can function as a VOR or as an ILS, depending on the frequency input into the control head.





*Figure 3.6.* CP140 TACAN.

The TACAN receiver provides navigation guidance to military TACAN sites. It is an analog system that can be coupled to the new digital avionics of the NFIMP systems.

## Chapter 4 – Test Methodology

The flight test program to evaluate the NFIMP cockpit upgrade on the CP140 Aurora aircraft was conducted in three phases. Phase one consisted of a comprehensive review of the system design documentation. Phase two included an initial familiarization session with the NFIMP systems, hands on training, preliminary system evaluations and feedback to the contractor. Phase two was carried out using a well-defined, methodical approach within two discrete time periods at the contractor's SIL. Phase three comprised the flight test phase of the test program, and consisted of 40 test flights out of Halifax International Airport. This three-phased approach proved to be a successful method of uncovering deficiencies that were embedded in the prototype systems. This chapter outlines the three phases, discusses the purpose of each phase and highlights the constraints, limitations and strengths of each phase.

The test philosophy was one in which human factors issues were seen to be very important and where relevant comments were collected in each of the phases throughout the test program. The test team was comprised of test pilots and flight test engineers who were formally trained to be human factors evaluators. The contractor had a human factors specialist, as did the Directorate of Technical Airworthiness (DTA) who were responsible for the airworthiness components of certification and provided oversight to the program.

### *Phase One – Document Review*

A comprehensive review of the NFIMP system design was a time consuming phase of the test program. As part of the document review, test team members examined contractual documents to understand the scope of the project and to decipher the specifications against which the system performance was being measured. The test team

also became intimately familiar with multiple test and certification guidance manuals such as the FARs, CARs, MIL-STDs, the Federal Aviation Administration ACs and the SAE ARPs as references of the human factors design requirements. The purpose of the documentation review was to understand the design philosophy, learn the functionality of the systems and to help focus the team on potentially problematic areas for further investigation during the subsequent phases of the test program. The review also provided an opportunity for the test team to identify potential deficiencies at the beginning of the test program and to offer feedback to the contractor up-front with the goal of minimizing overall program costs and schedule delays. Document review is an essential part of any test program, and was a logical lead-in and prerequisite for phase two of the test program.

#### *Phase Two – Systems Integration Laboratory*

Phase two of the test program to evaluate the NFIMP systems on the CP140 aircraft took place at the contractor's SIL. The SIL was created as one of the primary developmental tools for the contractor to verify and validate new software for the NFIMP program but it also proved to be an invaluable training aid and evaluation device for the test teams. Specifically, phase two consisted of two sessions in the SIL: the first being a two-day human factors evaluation in June of 2002; and the second being an NFIMP system familiarization course in January of 2003. Two reports were generated from the sessions: the first was a human factors evaluation interim report following the 2002 evaluation (Aerospace Engineering Test Establishment [AETE], 2002) and the second was a feedback report following the 2003 familiarization course (AETE, 2003). While these reports were presented to both the contractor and the sponsor, very little action was taken at the time. Lim, Long and Hancock (1992) refer to this as the "too little, too late"

phenomenon. An in-depth human factors analysis did not occur until the evaluation stage at which point many of the issues raised were determined either to be too costly and time consuming (“too late”) or any proposed solutions to the issues were nominal ones that did not sufficiently resolve the overriding concerns (“too little”). The sponsor was hesitant to pay for any significant changes that would delay the program and that would likely still require additional modifications after the flight tests were completed. The contractor was hesitant to change anything without additional funding. As a result, the reports assisted the test team in the creation of the flight test plan and the development of the test cards but did little to correct perceived design flaws early in the program. The test team made certain that the points raised in the preliminary evaluations were assessed airborne to either re-enforce these initial observations or to disprove them.

#### *SIL Description*

The SIL was a mock-up of the NFIMP systems for the pilot’s side of the CP140 flight deck and is shown in Fig. 4-1. The SIL included the EFDI, EHSD, DCP, Radar Altimeter (RADALT), TCAS, ACP and the Control Display Unit (CDU). The layout was not representative of the CP140 flight deck.

From the test team perspective, the value of the SIL was in its realistic modeling of the prototype systems, which facilitated learning the new functionality, allowed for hands on training, and provided early insight into any characteristics that might be undesirable in a flight environment. The NFIMP flight instruments and displays in the SIL were identical to those that were installed in the aircraft, albeit in a different configuration. Another advantage of the SIL was the ability to test not only the individual



Figure 4.1. CP140 SIL.

A mock-up of the pilot's displays and controls to include the EFDI, EHSI, DCP, CDU and the ACP at the Systems Integration Laboratory. The layout of the SIL was not representative of the cockpit layout in the aircraft.

components or sub-components but also the interfaces and interactions between the systems.

In the SIL, the systems under test were evaluated using both simulation and stimulation. This was significant and allowed the test team to evaluate not only the functionality of the systems through software manipulation (simulation) but also the operation of the genuine hardware components (stimulation). Simulation was performed when either the component itself or the signals, inputs and interfaces to the component were simulated through software. Stimulation was performed when the components of a system or its interactions with other systems were stimulated by the actual external inputs.

Statically, the SIL was able to stimulate the systems by interconnecting the actual aircraft equipment. For example, it was possible to operate the EFDI using the same inputs, interfaces, cabling and subcomponents that would be used on the aircraft. This meant that the EFDI was receiving inputs from the aircraft embedded GPS/INS (EGI) system (including a real-time global positioning system feed), the aircraft air data computer system, etc. This allowed the contractor and test team to fully evaluate the integration of all the systems in the SIL, significantly mitigating the program risk prior to flight test. A limitation of this configuration was that it could not be used in a dynamic “flight” environment. For example, when “flying” the SIL, the EGI platform was static and did not provide the flight displays with changes in aircraft heading and attitude information. In order to evaluate the systems in a dynamic flight environment, the NFIMP inputs in the SIL had to be *simulated*. It was important that the SIL be able to both stimulate all of the components in a static “ground” environment as well as simulate

the integration of systems while “airborne” to evaluate the functionality in a dynamic “flight” environment.

The ability of the SIL to both stimulate and simulate the NFIMP systems highlighted both the advantages and the limitations of the SIL. In practical terms, one of the main advantages of the SIL was the opportunity for the hands on application of the written procedures. The SIL also provided the sensory feedback to the test pilots that could not be obtained from reading the manuals, such as the tactile feedback of depressing a pushbutton. In addition, a significant advantage of the SIL was that it allowed for an in-depth fault analysis. The test team was able to pull circuit breakers and induce system failures to observe the system response and resultant feedback to the crew. The SIL also provided a valuable training environment for the flight testers to interact as a team and to develop crew procedures. This was an important objective and enhanced the safety of the test program. An additional benefit of testing at the SIL was that it brought together the flight testers and the design engineers. This created a forum for discussing design philosophy and in many cases created a direct feedback loop to the engineers when a system did not function as expected. The majority of the engineers did not fly on the test flights and did not have the operational insight of the test pilots. The SIL therefore provided a unique opportunity for the design engineers to validate their understanding of flight operations with the aircrew and to ensure that the implementation of their design met the desired objectives. Overall, the SIL provided an essential link between the instruction manuals and the operational use of the system.

One additional benefit of the SIL was the information transfer that occurred between the theoretical and visual domains. As stated in the famous proverb “A picture is

worth a thousand words” (Barnard, 1921), the SIL allowed the test team to visualize what was written in the system descriptions. For example, the SIL allowed the test team to evaluate the suitability of a size 14-font annunciation on a 4-inch display panel. In another case, the readability of a yellow caution annunciation was evaluated against a light blue background. Furthermore, the SIL showed how each subsystem was linked together and what information was displayed on each sub-page or screen. In summary, above all other benefits, the SIL training and evaluation helped to build the confidence of the test team that the NFIMP systems were mature, safe and ready for flight test.

Despite the usefulness of the SIL in preparing the test team for flight test, there were also some inherent limitations. One of the greatest shortcomings of the SIL was the fact that it was not a realistic representation of the CP140 Aurora cockpit. The SIL was not a replication of the Aurora flight deck but simply a panel with the new NFIMP systems and office chairs for crew seating. As a result, multiple human factors evaluation criteria such as reach and vision (readability, parallax) could not be assessed.

Furthermore, the NFIMP systems in the SIL were not oriented in the same way or situated at the same location as they were in the CP140 cockpit. This prevented the test team from assessing the layout and any related human factors issues, such as workload. A third major drawback to the SIL was the simulated flight environment, which prevented the evaluation of many operational tasks and the subsequent task workload analysis.

While an understandable limitation of the SIL, the low fidelity ‘flight simulator professional’ software was not a challenging or realistic flight environment. It was for these reasons that the final decisions on system compliance and a comprehensive human factors evaluation needed to take place in flight.



### *Phase Three – Aircraft Flight Test*

Phase three of the test program to evaluate the cockpit upgrade to the CP140 Aurora aircraft was the airborne flight test itself. This was the culmination of years of hard work by the contractor as well as extensive planning and preparations on the part of the DND and the flight test team. Phase three was the final assessment where every detail of the design would either be signed off as acceptable or rejected as a deficiency requiring further modification. The test team could now be definitive in their assessments after having finally observed the systems in an operational and dynamic flight environment. It should be noted that no changes were made to the NFIMP design following phases 1 and 2 of the test program, despite numerous recommendations. This was a decision made by the project office and not the preferred choice of the test team.

The airborne testing of the CP140 NFIMP systems followed a well-defined and scripted test plan (CMC Electronics Inc., 2004). The minimum flight crew consisted of two pilots, one Test Director and one data engineer. The Test Director, who was either a Flight Test Engineer or a Flight Test Navigator, controlled and orchestrated the test flight through the use of previously developed test cards. The test pilot flew the test points listed on the test cards and provided detailed comments on the ability of the systems to meet the test criteria.

Each of the test flights were restricted to six hours in accordance with the Canadian Forces Flight Test Orders (AETE, 2001), which meant that flights generally consisted of four hours of flight test plus transit time to and from the test area. All test points adhered to a 'build up approach' methodology whereby test points would always begin with the most basic of manoeuvres and increase in intensity and complexity. This

building block approach was employed system-by-system before assessing the integration of multiple systems as a whole. Human factors engineering and analysis were intrinsic parts of every test point and every aspect of the airborne flight evaluation. All test cards included a place to record the subjective comments and recommendations of the test pilot while executing each test point. The goal was to efficiently accomplish the test points in the safest and most expeditious manner, and anything that hindered this objective was recorded for subsequent discussion and analysis.

After each test flight, the test pilots discussed any observations with the test team to determine the significance of the comments. Any potential deficiencies that arose from the discussion were then evaluated in terms of the mission and role of the aircraft. For example, a quirk that was observed on a system sub-page was assessed against any impact on the safe or effective completion of the intended task. The reason for this was that if a noted deficiency had a minimal impact on the operations of the aircraft, then the severity of the deficiency would be downgraded and sometimes was disregarded altogether. If required, the test team would reference the human factors engineering guidance manuals for clarification or for a deeper analysis of the deficiency. These observations, discussion and analysis were then documented in a post flight report (PFR). PFR's were written for each and every flight by the test pilots and flight test engineers.

In addition to writing the PFR's, the test team submitted problem reports (PRs) through the project office to the contractor. These were reports that described what the test team perceived to be potential deficiencies. It allowed the test team and the contractor to track potential problems through a database that could be subsequently referenced to avoid recording duplicate snags, or deficiencies. It also served as a

configuration management tool to track the status of each snag and to note any efforts made towards resolution of the snag. The data from the PR database and the data from the PFRs were the primary sources of information for the description and analysis of the deficiencies discussed in this paper.

## Chapter 5 – Results and Discussion

### *General*

The findings presented in this chapter are primarily based upon the observations and expertise of the test pilots and flight test members that were tasked to evaluate a partial glass cockpit upgrade to the CP140 aircraft. Numerous deficiencies were identified through the comments and critiques of the test team. Often these deficiencies were singled out due to their propensity to cause human errors, or in the opinion of the test team, they would significantly increase the probability of a human error. The purpose of this chapter is to analyze these deficiencies from a human factors stand point to uncover underlying causal factors that could lead to or contribute to human errors. Once identified, potential solutions are offered based upon the same human factors engineering principles that were used to highlight the deficiencies.

### *Deficiency One – Autopilot and Flight Director (AFDS) Loss of signal*

#### *Results*

The feedback to the pilots of a loss of signal when the AFDS was engaged and coupled to a navigation source was unclear and created confusion. From the signals given, the pilot was unable to quickly and correctly interpret the information provided on the EFDI so as to effect the appropriate actions in a timely manner. In addition, the feedback was not always immediately perceived by the pilot, which compounded any problems created by the signals' lack of clarity.

When coupled, the AFDS could fly the aircraft using a navigational aid as the guidance source. The EFDI was the pilot's primary flight display and presented the status of AFDS modes to the pilot in his primary field of view (see Figure 5.1).

Whenever the AFDS was coupled to a navigational aid and the signal was temporarily or permanently lost, the indication to the pilot was a flashing green annunciation on the EFDI. The reasons for the lost signal varied from normal operations (such as a station overflight and the subsequent passage of the navigational aid) to degraded AP modes or system failures. Regardless of the reason for the loss of signal, it was difficult for the pilot to distinguish between the initial capture of a navigational source, a normal but temporary loss of signal and a permanent loss of signal due to a degraded mode or failure state. The problems associated with this design are discussed below.

### *Discussion*

For ease of explanation, the TACAN navigational aid will be referred to extensively as one example that illustrates several of the issues that arose concerning the operator-machine interface between the pilot and his primary flight display (EFDI) with reference to the AFDS navigation status. During testing, there was confusion in the cockpit when the annunciation for the coupled navigation mode began to flash on the EFDI. The flashing alone was an ambiguous signal that did not clearly alert the pilot to the current autopilot state. As a result of this ambiguous signal, the pilot was unsure what the autopilot would do next and therefore would either fail to respond to the degraded mode of operation or would respond too late. In many cases, the aircraft diverged from

Roll mode engaged in navigation mode (coupled to the TACAN)

AFDS status showing autopilot and flight director engaged and coupled



Pitch mode engaged in altitude hold

Figure 5.1. CP140 EFDI showing the AP and FD System status.

the desired track and required the pilot to intervene to prevent an unsafe situation from developing.

The sub-paragraphs below describe the four scenarios that caused a green TCN indicator to flash.

1. Initial Capture. A green TCN illuminated and flashed for five seconds on the EFDI when the following two requirements were met: first, the navigation mode had to be selected on the ACP; and second, the TACAN radial was captured for the first time. This indicated to the pilot that the autopilot had successfully captured the signal and would now track the desired course.
2. Temporary interruption of signal. During a temporary interruption of the navigational signal, the indication to the pilot of this modal state on the EFDI was also a flashing green TCN annunciation. This situation was especially common on the CP140 aircraft because of the way the TACAN antennas worked. On most aircraft, a temporary loss of signal would be a rare occurrence but on the CP140 it was common, particularly while manoeuvring gently within the terminal area. There were two TACAN antennas on the CP140, one on the upper fuselage and one on the lower fuselage. There was no automatic switching matrix and therefore the pilots had to manually select the top or bottom antenna. A temporary loss of signal was normally, but not always, corrected by selecting the alternate antenna. When the green TCN signal began to flash, the AFDS transitioned into the heading hold mode, which was a dead-reckoning mode. The fact that the AFDS was then operating in a heading hold mode was not annunciated on the EFDI (or anywhere else in the cockpit). Simultaneously, the AFDS attempted to reacquire

the lost signal as if the navigation mode had just been armed but this was not communicated to the pilot either. The TCN annunciation would continue to flash until the signal was recaptured. If it could be immediately determined that the signal loss was due to an incorrect antenna selection, the signal was quickly regained and the AFDS was able to recapture the signal and the aircraft continued to track towards or away from the station. Whenever the signal could not be immediately regained, however, the AFDS failed to recapture the signal and the aircraft would diverge from the desired track with no warning provided to the crew. Since the indication for loss of signal was the same as the indication for signal capture, several seconds would pass as the pilots assessed the potential causes of the flashing green TCN annunciation. The time required to analyse the causes of the flashing green TCN annunciations was such that the aircraft had drifted sufficiently far off track to prevent the AFDS from re-acquiring the selected TACAN source. This situation was further complicated by the fact that a station overflight (discussed in paragraph 3 below) was annunciated in exactly the same way as the temporary loss of signal. For the pilot, it was impossible to distinguish between these three events.

3. Station Overflight. Station overflight was a normal occurrence and is common to all aircraft and navigational aids. Station overflight is a phenomenon that modern avionics systems are designed to accommodate, including the CP140 AFDS. One of the problems with the design on the CP140, however, was an unclear indication of this state to the pilots, which led to confusion with other modes. There was a 'cone of confusion' where the bearing information was unavailable as the aircraft



overflow the navigational station. This was essentially an area directly above the station that formed the shape of a cone with the station being the focal point of the bottom. The diameter of this cone was dependent upon the aircraft altitude and therefore the higher the aircraft altitude, the greater the distance from the station the aircraft would be when the signal was lost. The cone could range anywhere from 60 to 110 degrees, depending on the ground station and would be 12nm in diameter at 36,000 ft (DND, 2003c). While in the cone of confusion the AFDS transitioned to the heading hold mode. Similar to the temporary loss of signal described in subparagraph 2 above, the fact that the AFDS was now operating in a degraded heading hold mode was not annunciated to the pilot on the EFDI, nor anywhere in the cockpit. The sole indication to the pilot that anything had changed was a flashing green TCN annunciation, which could have indicated any one of a number of modal states. During the flight test trials, when the aircraft passed through the cone of confusion, the AFDS was sometimes able to recapture the desired track on the other side of the station but at other times it was not.

4. Component failure. When a component failure of the TACAN occurred, the indication to the pilot on the EFDI was a flashing green TCN annunciation. A ‘failure’ in this instance could be characterized by any number of failures associated with the navigation source. Some examples would be the failure of the power source to the receiver, a popped circuit breaker, an incorrect channel dialled into the control head or a faulty antenna.

When the design methodology for the flashing annunciator was assessed from a human factors perspective, several undesirable characteristics were revealed. First, the

annunciation to alert the pilot that there was a loss of signal was the same annunciation used to inform the pilot of a positive mode capture. The system failed to distinguish between these two significant and very different events. It is critical that pilots are able to discriminate between different autopilot modal states, particularly ones that are cautionary in nature and result in unexpected aircraft guidance. Palmer et al. (1995) state “Status indications should permit the flight crew to quickly and easily distinguish between normal and non-normal situations.” This was not possible when different control states provided the same, or similar, feedback to the pilot. In addition, it was not possible using the CP140 autopilot modal display feedback for the pilot to differentiate between the different scenarios outlined in sub-paragraphs 2, 3 and 4 listed above. Knowing the cause of the loss of signal (temporary interruption, station over-flight or component failure) would enhance the pilot’s situational awareness and could alter his response.

Second, the annunciation to alert the pilot to a degraded mode of operations was green, which in this case, was the fact that the autopilot was no longer tracking the selected navigation source. Federal Aviation Regulations (U.S. Department of Transportation, n.d.) and Canadian Aviation Regulations (Transport Canada, 2002) spell out the guidelines for the use of colour coding in glass display systems. Similarly, the US Department of Defence military standards specify a colour-coding scheme for use in visual displays in which green indicates a fully operational system (Helander, 1987). In simple terms, green, yellow and red are the most well defined colours in use in visual displays. Green should be consistently used to denote ‘good,’ yellow to denote ‘caution’ and red to denote ‘danger.’ After discussing the use of colour in aviation displays, Aragon and Hearst (2005) state that these “color meanings are conventional and widely

accepted in the aviation world” (p. 444). After discussing the various regulations concerning colour conventions, Don Harris (2004) summarizes them by saying “in general, green is ‘good,’ red is ‘bad’ and yellow is ‘potentially bad’!” (p. 74).

Considering these regulations and reports, green was a poor choice to indicate to the pilot that the AP had shifted into a reversionary mode. The fact that the AP had, on its own, transitioned into a degraded mode of operations reflected an abnormal state and the pilot should have been quickly and accurately advised of this critical change. A more appropriate colour to notify the pilot of the failure of the navigation source, a loss of signal due to a station over-flight or a temporary interruption of the signal would be yellow.

Third, the annunciation to the pilot lacked sufficient detail regarding the cause of the change in status. This was especially true due to the fact that the change in status was not commanded by the pilot but rather was a mode reversion due to the loss of the guidance signal. Therefore, it was important to provide salient data regarding the signal loss to the pilot in an unambiguous and easy to understand format. Palmer et al. (1995) discuss the importance of situational awareness obtained from the displays and stress that “the flight crew should always have access to information about what the various on-board systems are doing and that access should be appropriate to the current pilot responsibilities” (p. 24). This additional information would provide the pilot with enhanced situational awareness and prevent the pilot from looking elsewhere inside the flight deck, searching for clues as to the cause of the apparent failure. Since the pilot’s response is dependent upon the cause of the reversionary mode, this information is especially important. For example, if coupled to a TACAN navigation source, a

temporary interruption to the signal would cause the pilot to immediately select the alternate antenna. In the case of the station over-flight, the pilot would either increase his monitoring time on the EFDI (to see if the autopilot recaptured the desired outbound radial) or switch to the heading select mode (to steer the aircraft onto a new outbound radial). A failure of the receiver itself would result in the pilot selecting an alternate navigation mode. There is a balance between providing too much information, which can also cause problems (Wickens et al., 1995) and providing concise and salient cues to the pilot to ensure adequate situational awareness and an appropriate and timely response (Sarter et al., 1995).

Finally, a flashing signal was not always sufficient on its own to draw the pilot's attention to a mode change. There is an inherent trust that is afforded to automated systems. Automation complacency can set in as a result and the monitoring of these automated systems during extended periods of time and can result in a vigilance decrement or an increase in response time (Masalonis et al., 1999). A vigilance decrement is the term used to describe a decline in the detection rate of critical signals with increased time on task. Nikolic et al. (2005) argue that the onset or flashing of a display element to capture a pilot's attention and advise him of a mode transition is not always successful. This is partly due to the data rich, event driven environment of aviation displays as well as the difficulty in capturing a pilot's attention when his attention may be focused on another task. "Visual onsets may be effective when they appear in isolation and in the context of spartan displays and tasks, however, they do not seem to be sufficiently salient to capture attention when pilots are already engaged in some other attention-demanding tasks" (Nikolic et al., 2001, p. 5.A.3-2). While the

flashing display element was a good way to signal a mode transition, it was insufficient on its own. Other methods that could assist in capturing the pilot's attention would be the use of colour changes, attention cueing in multiple locations and auditory signals.

There were several human factors problems associated with the annunciation of a loss of signal to the AFDS. These were ambiguous cues, poor use of colour logic, insufficient information during uncommanded mode changes and a lack of attention capture cueing. The current design provided limited information to the pilot to make timely decisions and ensure adequate situational awareness. The outcome could be a delayed response, or in the event the cue was missed, no response at all. Some of the potential consequences could include an ineffective instrument approach, an excursion out of protected airspace or even a collision into terrain, as occurred in the crash of a Boeing 757 aircraft near Cali, Columbia in 1995 (NTSB, 1995).

The preceding paragraphs have identified the underlying cause factors for potential errors related to the AFDS as an inability to easily discern between different modal states (ambiguous information), misleading colour coding of the display element, a lack of salient information to the pilot during status changes and insufficient methods of alerting the pilot to reversionary modes.

### *Recommendations*

The use of a green display element to alert the pilot to a failed or reversionary autoflight mode was deemed unacceptable by the flight test team. Using the same annunciations to represent different modal states was also deemed unacceptable. The reasons or causes for the change of status of the autoflight mode must be readily apparent

to the pilot. The pilot must be able to quickly and easily perceive any change in the status of the autopilot mode during all flight regimes. These are not deficiencies that can be addressed through training or the strict use of standard operating procedures. Therefore, the operator machine interface between the EFDI and the AFDS to reflect the loss of signal of a navigation source should be redesigned. The first change in the redesign should be to implement unique status indications on the pilot's primary flight display, for each autopilot mode or sub-mode, to ensure that no two modes could be confused. The second change should be the inclusion of supplemental information during status changes to allow the pilot to identify the correct reversionary mode. A modification such as this would provide the pilot with excellent situational awareness and allow him to make the right decisions and take the appropriate actions. Any additional information would need to be succinct but would have the added benefit of distinguishing different modal states. In addition, the colour schema should be re-examined. Given appropriate supplemental information, green could be an acceptable colour during certain status changes such as a station overflight. During reversionary modes, however, yellow would be a more suitable colour choice, and during any failure modes, red would be the most appropriate colour. Finally, auditory cueing should be considered an indispensable component of any autopilot system, especially during degraded operations. Voice cueing and unique tones for autopilot use are standard features in the commercial aviation industry. The addition of an aural cueing system on the CP140 autopilot and flight director system would provide the additional safeguards required for the demanding military operations required of this platform and ensure that a change in modal status would not be missed by any of

the flight deck occupants. All of these recommendations are supported by common systems that are employed in commercial aviation.

While advanced and highly automated systems such as the Boeing 777 and Airbus A340 provide effective examples, smaller platforms such as the Bombardier Challenger CL604 aircraft also employ these same human factors principles. In the CL604, if a signal were lost, the autopilot would revert into a dead reckoning mode of heading hold and attitude hold. The annunciation would change from green to white to indicate the system was no longer following the desired course and would be accompanied by an appropriate aural tone. In addition, a large X would appear in the course window and a red navigation flag would be present. During a station overflight, the system would simply stay in the selected navigation mode and would be capable of reacquiring the desired outbound track. During a degraded mode such as a system failure, the autopilot would disengage, accompanied by a “cavalry charge” aural tone and a slew of red failure flags (Captain Dave Scott, personal communication, February 21, 2007). This feedback design would be sufficient for the pilot to quickly determine the correct autopilot modal state and maintain a satisfactory level of situational awareness.

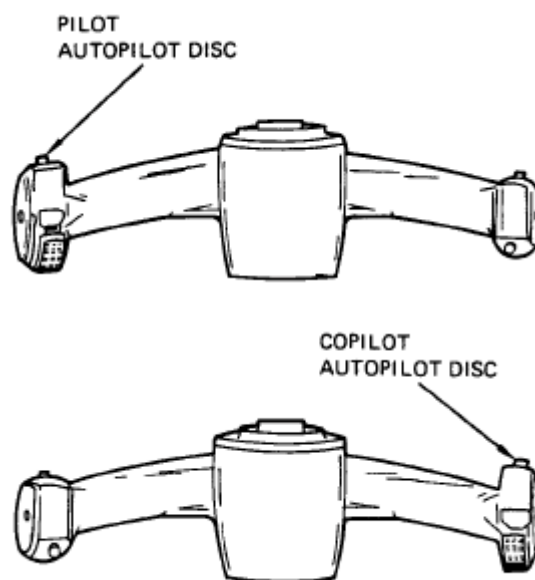
#### *Deficiency Two – Automatic Flight Control System (AFCS) Disengagement*

##### *General*

During the flight test program there were several deficiencies regarding the disengagement of the AFCS, or autopilot (AP). The deficiencies related to indications of both normal and non-normal disengagements of the AP. There were multiple methods of disengaging the AFCS and each could be categorized in one of two ways: normal or non-

normal disengagements. Recall that the only method of achieving a ‘normal’ disengagement of the AP was by depressing the autopilot disconnect switch on the outer horn of the pilot or co-pilot control wheel to the second detent (the first detent temporarily disengaged the altitude hold mode) as shown in Figure 5.2.

A ‘non-normal,’ or ‘abnormal,’ disengagement was achieved by either depressing the AP engage pushbutton on the AFDS control panel (Figure 3.1), pulling the AP emergency disconnect handle (Figure 5.3) or by any number of system failures or malfunctions.



*Figure 5.2.* Automatic Flight Control System Disconnect Switches.

Top view of CP140 control wheels showing pilot and co-pilot autopilot disconnect switches.



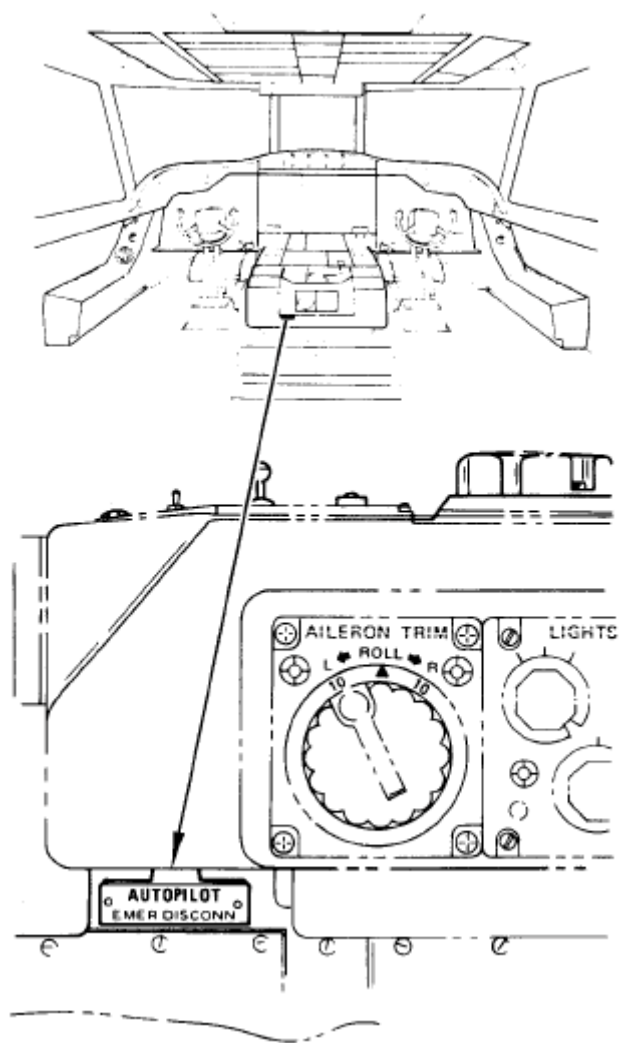


Figure 5.3. AP emergency disconnect handle.

During the test program, the test pilots commented that it was not always clear that the AP had been disconnected and there were opportunities for confusion following either a normal or non-normal disengagement. Specifically, sometimes the normal disconnects were missed and the non-normal disconnects were ambiguous. This resulted in a lack of situational awareness and uncertainty, often during a critical phase of flight.

### *Results*

#### *Normal Disengagement*

A normal disengagement was commanded by either the pilot or co-pilot through the disconnect switch on their respective control wheels. The only feedback to the pilot or co-pilot on the EFDI of a normal disengagement was the disappearance of the green AP symbol (Figure 5.4 and Figure 5.5).



*Figure 5.4.* CP140 EFDI showing AFDS status prior to AP disengagement.



Figure 5.5. CP140 EFDI showing AFDS status following AP disengagement.

#### *Non-Normal Disengagement*

A non-normal disengagement referred to a disengagement of the AP by any means other than the pilot or co-pilot control wheel disconnect switches. These non-normal disengagements included depressing the AP ENGAGE pushbutton on the ACP (could be done from either the pilot or co-pilot seat), actuation of the AP emergency disconnect handle (from the pilot seat or flight engineer seat) or any number of system failures or malfunctions such as a miscompare between the two AP channels or a failure of the AP power source. A non-normal disengagement was indicated by a flashing of the AP and radar altimeter warning lights (referred to as the AFCS/RAAWS warning lights) in addition to the disappearance of the green AP display element. The AFCS/RAAWS

warning lights had a dual purpose: They were warning flashers to indicate a non-normal disengagement of the AP in addition to providing altitude warnings associated with the radar altimeter system. These lights are discussed in more detail below. See Figures 5.6 and 5.7 for the location of the AFCS/RAAWS warning lights on the pilot and co-pilot instrument panels.

### *Discussion*

#### *Normal Disengagement*

The flight deck indications of a normal autopilot disengagement were subtle and could be missed by the non-flying pilot if he were distracted, pre-occupied with another task or was experiencing a decreased state of situational awareness. The disappearance of a small AP display element was not easily noticed unless the operator was directly focused on the display and in some cases, even direct attention failed to pick up the disappearance of the small symbol. Recall from Chapter 2 that Wickens et al. (1989) discuss the dangers associated with the absence of cues as a form of modal feedback by pointing out that the people will more easily notice an active annunciation rather than observe the absence of something. (p. 122).

One of the primary roles of the non-flying pilot is to provide back up for the flying pilot, so it is critical that both pilots maintain a high level of situational awareness at all times. Having both pilots in the loop and cognizant of the current state of the aircraft is a critical aspect of the safe operation of a multi-crew platform. In discussing human error in aviation, David Nagel (1989) refers to a comprehensive analysis of aircraft accidents over a 24-year period that was conducted by R.L. Sears in 1986. The



Figure 5.6. Pilot's instrument panel equipment layout showing the AFCS/RAAWS warning lights in the top left hand corner.



Figure 5.7. Co-pilot's instrument panel equipment layout showing the AFCS/RAAWS warning lights in the top right corner.

analysis showed that an inadequate crosscheck by the second crewmember was a significant cause factor in 26 percent of the accidents. Crew related issues were attributable to 51 percent of the cause factors. Billings (1981) examined more than 12,000 flight incidents where a problem in the transfer of information involving flight deck members was implicated in 73 percent of the incidents. These and other studies are evidence that it is critical that all members of the flight deck are aware at all times of the status of the aircraft, particularly when using automated systems as was illustrated by the crash of the L1011 aircraft into the Florida everglades in 1972. As a result, most commercial systems use both visual and aural means of notifying the pilot of an autopilot disengagement, including the system used on the CL604 Challenger as well as the system used on the A310 Airbus (Captain Steve Chalkley and Captain Dario Rossi, personal communication, February 13, 2007).

#### *Non-Normal Disengagement*

A non-normal disengagement could result from one of two things: either an uncommanded disconnect due to a system malfunction; or, an operator commanded emergency disconnect as described in the aircraft operating instructions manual (DND, 2003b). From a human factors perspective, a flashing red eyebrow light would generally be considered an acceptable method of advising the flight crew of a potential emergency situation. There were two problems, however, with the use of the AFCS/RAAWS warning lights as the primary mechanism to alert the flight deck to an emergency situation. One problem was that the red warning lights flashed when the pilot disengaged the autopilot using the AP ENGAGE pushbutton on the ACP. The second, and more

significant issue, was that the red AFCS/RAAWS warning lights would flash for multiple non-emergency related reasons and this would occur on a regular basis.

The CP140 flight manual categorized autopilot disconnects into normal and non-normal conditions. A non-normal disengagement did not always equate to an emergency situation and yet always elicited a red flashing annunciation for a response. The annunciations for an emergency should be unique to the situation and easily discernible by the pilot. This philosophy is inline with standard human factors principles (Salvendy, 2006) and corresponds to industry standards that are employed on such aircraft as the CL604 Challenger (Captain Dario Rossi, personal communication, February 13, 2006).

The second issue of using the same red flashing lights to alert the pilot to both a non-critical and critical situation is a more serious one. In addition to alerting the crew to a non-normal AFDS disengagement, the AFCS/RAAWS flashers would flash in the following circumstances:

1. An altitude deviation of more than 60 feet when in the altitude hold mode;
2. Any time the aircraft descended through an altitude preset on the radar altimeter;
3. Each time the aircraft descended below 400 feet (ft) above ground level (AGL) with the landing gear up and locked; and,
4. Continuously below 200 ft AGL when the landing gear was up and locked.

In addition, for operational sorties the CP140 Aurora standard operating procedures (SOPs) demanded setting the radar altimeter warning pointer at multiple step down altitudes for every descent (and there were many descents during each operational mission). The result was the frequent illumination of the RAAWS flashers during each



flight. Furthermore, false warnings from the sensors were noted to be a relatively common event. The result was that the pilots had become so desensitized to the warning flashers that their illumination was not seen as an emergency situation and was often not even cause for alarm. In a recent CP140 flight safety incident (FSIS, 2005), a crew observed the illumination of both the pilot and co-pilot RAAWS flashers while descending into an area they believed to be over water. Both pilots noticed the warning indicators but continued to descend, believing them to be false warnings. The flying pilot caught a glimpse of some trees through a break in the clouds, realized they were over land and immediately initiated a climb. They were flying in mountainous terrain and the incident could have easily resulted in a ‘controlled flight into terrain’ accident. In a separate flight safety incident (FSIS, 1997) a crewmember from the aft portion of the aircraft averted a crash when he alerted the pilots to the aircraft altitude of 120 ft ASL. The pilots were flying operationally at night in a steep turn and did not realize that the autopilot had become disconnected and that they were descending, even though both of the eyebrow warning lights were flashing. While the flashing lights are significantly more effective than no lights at all, they are insufficient in their current implementation. Palmer et al. (1995) are clear in their design philosophy that different alerts should sound and appear dissimilar and that “critical alerts should be presented aurally, since sounds don’t require directed attention” (p. 29). Flanagan et al. (1998) point out additional advantages of an auditory system in that they essentially offer an “unlimited field of view” (p. 1).

The lack of a unique auditory warning system for the emergency disengagement of the autopilot on the CP140 is an unacceptable situation. Incidentally, the legacy system had an auditory signal associated with the disengagement of the autopilot, albeit

unintentional. “A number of studies have focused upon the use of auditory enhancements for visual displays. Early research has indicated that subjects attend to auditory warning signals faster than visual warnings and it has been suggested that auditory warning signals are particularly useful for situations in which the visual system is overburdened” (Dry et al., 2005, p. 15). Nikolic et al. (2004) clearly submit that aviation flight displays are heavily saturated and argue this is one of the reasons why pilots sometimes miss alert cueing.

### *Recommendation*

#### *Normal Disengagement*

The elimination of any ambiguity associated with the normal disengagement of the autopilot could be accomplished in a variety of ways. The recommended solution is the addition of an auditory cueing system. The addition of unique and distinguishable tones or word phrases to alert all members of the flight deck to the fact that the autopilot is no longer flying the aircraft would be ideal. An alternate but inferior solution would be to embed a procedural requirement for the flying pilot to clearly articulate to the crew when the autopilot is being disconnected. One of the limitations to such a solution is that it would still fail to warn the crew in the event of an inadvertent disconnect, as was the case in the L1011 crash into the everglades (NTSB, 1972). There are also tangible benefits to minimizing the number of rules, regulations and procedures that the crews are required to remember. This relates to the basic human limitations of memory and cognitive processing. Furthermore, the CP140 has seven radios onboard and their operations dictate frequent communication. As a result, anything that can be done to

minimize transmissions on the intercommunications system on the CP140 should be done whenever possible. The best option to correct this deficiency, therefore, is the implementation of an aural cueing system.

#### *Non-normal Disengagement*

The solution offered to correct the issues associated with a normal disengagement would also solve the problems associated with a non-normal disengagement. Due to the potentially critical nature of an autopilot disengagement and the importance of a timely response, an auditory cueing system should be implemented on the CP140 aircraft. Such an auditory cueing system should be unique to the autopilot and not represent multiple systems, as was the case with the flashing AFCS and RAAWS warning lights. This would provide the pilot with sufficient information to determine an appropriate course of action and to ensure that there was no confusion amongst all crew members.

#### *Deficiency Three – Unselected Approach Guidance*

##### *Results*

Early on in the flight test program, it was observed that approach guidance for either a precision instrument landing system or a localizer back course approach was being displayed on the pilot and co-pilot EFDI displays when the pilots had not made this selection on the DCP. This was a clear violation of the basic rule that the human element must always know what the automation is doing (Palmer et al., 1995). As well, from the test pilot's perspective, this was a confusing design and the additional information was distracting and often irrelevant. The test team believed this to be a software bug but

follow-on discussions with the contractor revealed this to be the design intent. This design was a workaround for other system limitations and was meant to assist the flying pilot when transitioning from the initial approach segment using the avionics management system (or AMS) to the final approach segment of either an ILS or LOC(BC) approach. In the NFIMP design, moving the course source selector on the DCP from the AMS selection to the VOR selection as the pilot transitioned from the initial approach segment to the final approach segment caused a complete disengagement of the autopilot, including the illumination of flashing red warning lights. The contractor correctly foresaw this to be highly undesirable, especially in a critical phase of flight. As a workaround, the system was designed such that anytime an ILS or LOC(BC) frequency was dialled into the VOR/ILS control head, indications of glideslope, localizer and ILS/LOC(BC) display elements would be sent to the pilot and co-pilot EFDIs (see Figure 5.8). This would allow the pilot to fly an instrument transition on his EHSDI, while still receiving ILS guidance on his EFDI for an easy transition to the final approach segment (Jim Hastie, personal communication, February, 2005). There are some potential implications to this design that will be expounded upon in the discussion below.

### *Discussion*

From a human factors perspective, there were some concerns with a system that provided information on a primary flight display that was not commanded by the pilot or co-pilot. It is important to note in this discussion that the EFDI was designed to display ILS or LOC(BC) information anytime an ILS or LOC(BC) frequency was resident in the VOR/ILS control head, regardless of whether or not an ILS or LOC(BC) existed at that



*Figure 5.8.* CP140 EFDI with approach course selected to TCN on the DCP.

In this screen capture the magenta flight director bars in the center of the EFDI show guidance to the TCN station while the magenta diamonds on the left side and bottom of the display show guidance to the ILS approach.

particular airport. If the receiver was receiving a valid ILS or LOC(BC) signal, then this information would be displayed on the EFDI. If the receiver did not receive a signal, the EFDI would show a boxed yellow indication to reflect a failed or degraded state (See Figure 5.9).

For example, if the CP140 departed an airfield that had an ILS approach, the ILS frequency for the active runway of the departing aerodrome would be input into the VOR/ILS control head in the event the aircraft needed to return for landing. The AMS or TCN might be selected as the primary source for navigation. On departure, the aircraft would display valid, although irrelevant, ILS information on the pilot and co-pilot EFDIs. Once the aircraft was out of range of the ILS transmitter, the EFDI would provide feedback to indicate a failed or degraded ILS system. This symbology would remain on the EFDI enroute to the next airfield. If the subsequent airfield had no ILS approach, the failed indications would remain. The only ways to remove the indications from the EFDI would be to ensure that there was no ILS or LOC(BC) frequency in the VOR/ILS control head or to turn the VOR/ILS receiver off.

There were two specific problems with this design. The first was that it contributed to display clutter, while the second, and more significant problem, was that it had the potential to provide confusing and misleading information to the pilots. In their chapter on Aviation Displays, Stokes et al. (1988) described in detail many of the problems that can arise from “information overload in the cockpit” (p. 387). There are limitations as to the amount of information that humans can process, and in data rich environments such as aviation, our visual systems can quickly become overwhelmed. In the transition to glass cockpits, designers sometimes go too far in saturating the visual



*Figure 5.9.* CP140 EFDI showing both TACAN and ILS approach symbology.

In this screen capture the TCN is selected for course guidance. The ILS is not selected but is displayed because there is an ILS frequency in the VOR/ILS control head (no valid signal).

domain simply because the capability exists, without taking into account the cognitive repercussions. Wiener (1989) discussed this phenomenon in the context of advanced cockpit automation and suggested that the responsibility for resolution ultimately falls back in the lap of the human factors practitioners “to persuade designers to return to the fundamental question: What information does the operator need, and in what form should it be displayed?” The usefulness of displaying the unselected ILS information would be limited to the short period of time as the pilot transitioned from the enroute navigation source to the final approach guidance. In all other circumstances, this information would be irrelevant. Further studies have shown that close visual clutter can decrease the perceptual acuity of other more relevant visual cueing (Wickens et al., 1995).

The second problem with providing the pilot with unselected approach guidance on his primary flight display was that it provided him with confusing and misleading information. It failed to ensure the pilot was aware of what active guidance the automation was providing and provided negative training to the pilots by conditioning them to ignore flight guidance information on their primary flight displays. This negative training could create hazardous habit patterns that could result in unsafe acts (Shappell et al., 2000). There is a high probability that pilots will make significant errors when they learn to ignore information being presented to them, as was manifest in a 2005 CP140 flight safety incident (FSIS, 2005). Recall that through training procedures and poor design, over time the flight crew had become accustomed to ignoring the red flashing AFCS/RAAWS warning lights and almost flew the airplane into a mountain (discussed under deficiency two, in the discussion section for non-normal disengagements). With the complexity of modern displays, it is more critical than ever that any information provided



to the pilot be important and relevant information. By teaching pilots that they need to be selective about what is important and what can be ignored, the designers are increasing the pilot's cognitive processing requirements and therefore increasing the probability of making errors. Simultaneously displaying guidance to two separate approaches will create confusion and ambiguity, and at some point, will result in human error.

### *Recommendation*

The NFIMP prototype that displayed unselected approach guidance on the pilot's and co-pilot's primary flight displays was unacceptable. It is essential that in any design the pilot must either directly command the information to be displayed on his primary flight display or be clearly advised whenever new information is presented or altered (in a fully automated system). If more than one source of guidance is shown, then it must be clear what the primary or active guidance system is.

There are many ways of creating a safe and effective navigation and approach guidance system on a pilot's primary flight display. One system that is employed on the Fokker 28 aircraft permits the pilot and co-pilot to set up different approach or navigation guidance on their individual displays. While the pilot is navigating to the airport using one set of navigational tools on the pilot display, the co-pilot sets up the appropriate guidance for the instrument approach on the co-pilot display. When the pilot is ready to transition over to the instrument approach, there is a capability for the pilot and co-pilot to simply swap displays (Major Pete Haggins, personal communication, October 11, 2006). The CL604 Challenger aircraft has a NAV to NAV transfer functionality whereby the pilot can simply tell the Flight Management System that it wants to fly the ILS

approach following the current transition. The approach mode needs to be armed and when the ILS signal is acquired, the system smoothly transfers over to the ILS approach. This can be done manually as well (Captain Dario Rossi, personal communication, February, 2007). On the CP140, manually switching the navigation courses would cause a complete disengagement of the autopilot, which is unacceptable. The Fokker 28 and the CL604 provide just two examples of the many possibilities to overcome this deficiency that are being used in industry that are both practical and credible.

Regardless of the solution decided upon, it is clear that some form of re-design of the system is required. It should only be possible to display one set of approach guidance to the pilot at a time. As well, the ILS or LOC(BC) information should only be displayed when commanded by the pilot. Any new design should use a human-centered philosophy to ensure that the pilot is the focal point of the model.

*Deficiency Four – Coupled versus Uncoupled status of the Autopilot and Flight Director System (AFDS)*

*Results*

Modal awareness has become an industry wide issue. With the proliferation of modes in today's modern flight displays, it is a challenging task to ensure that both pilot and co-pilot are always cognizant of the current status of the autoflight mode. While this task of ensuring adequate situational awareness is a challenging one, it is also an essential one. "In all cases, the display should clearly and unambiguously indicate the current mode. For critical functions such as flight control, where mode confusions can cause

accidents, the mode indications should be given redundantly in several locations and with several types of cues” (Palmer et al., 1995, p. 24).

On multiple occasions during the flight-testing of the AP system, the test pilots were unable to identify the correct AP mode by reference to the primary flight display. On several occasions the test pilots were also incorrect when describing expected AP behaviour. Similar responses were obtained from operational pilots that were placed in the seats. The pilot’s confusion concerning the AP’s modal state represented what Sarter et al. (1997) referred to as automation surprises and could lead to mode errors. Mode errors are “inherently a human-machine system breakdown, in that it requires that the users lose track of which mode the device is in (or confuse which methods or actions are appropriate to which mode)” (Sarter et al., 1995, p. 6). An example on the CP140 NFIMP prototype design that demonstrated this breakdown in modal awareness was the determination by the pilot of a coupled or uncoupled AP mode with reference to the primary flight display.

### *Discussion*

The AP was always engaged in one of two modes: It was either coupled (combinations 2 or 5 from Figure 3.1) or it was uncoupled (combinations 1, 3 or 4 from Figure 3.1). The term coupled meant that the AP system was receiving steering guidance signals from the AFDC and was, in turn, controlling the movement of the flight control surfaces to follow those guidance signals. While in the coupled mode, the AP system was flying the airplane independent of the pilot’s input. The term uncoupled meant that the AP was maintaining pitch attitudes and bank angles set by the pilot but was not following

any specific steering guidance. In the uncoupled mode, the AP was assisting the pilot but was not independently flying the airplane. From a human factors perspective, from a safety perspective and from an evaluation perspective, it was essential that the test pilot be able to quickly and accurately determine whether the AP was flying the aircraft or not with reference to his primary flight display.

The coupled and uncoupled AP states were presented in different ways on the pilot and co-pilot primary flight displays, depending on which other modes were engaged. As a result, a comprehensive understanding of the AP system was required by the pilots to interpret the various display combinations. The effect was a relatively high level of cognitive activity to grasp what should have been a very intuitive and simple to understand annunciation of the current mode. In a series of studies of pilot-automation interaction, Sarter et al. (1995) found that “most of the observed difficulties were related to lack of mode awareness and to gaps in mental models of how the various automated modes work and interact” (p. 11). In modern cockpits, every effort must be made to keep any information provided to the pilot in the simplest and most usable form. This takes into account human limitations and is of greatest assistance to the pilot. A display that is easy to understand and interpret reduces the number of cognitive tasks required by the pilot and reduces the potential for mode errors. This subsequently reduces the probability of the pilot committing an error and increases the effectiveness of the overall system.

The primary flight display was capable of displaying a small bar to indicate a coupled state. As well, the ACP had a coupled annunciation. These were designed to assist the pilot but their application was not always consistent and therefore the coupled

indications were sometimes the cause of the confusion. The five possible AFDS combinations (see Table 3.1) are described below.

When the AP was first engaged, it activated in its most basic mode of heading and roll control (combination 1 from Table 3.1 and Figure 5.10). In this mode, the coupled bar was not illuminated on the pilot's primary flight display (PFD) but it was illuminated on the ACP (Figure 3.1). This was inconsistent and would have been more intuitive if both indications always reflected the same status. This was interpreted to mean that while it was not actively coupled to any outer loop flight guidance, it would couple to the flight guidance upon selection of an outer loop, or active guidance, mode.



*Figure 5.10.* CP140 EFDI engaged in the basic AP mode.

In this screen capture, the autopilot is not coupled to any flight guidance and is simply maintaining the pilot's last input in pitch and roll attitude.

The next AFDS combination was a coupled AP (combination 2 from Table 3.1 and Figure 5.11) where outer loop modes, such as the TACAN and altitude hold modes, had been engaged. Again, the pilot's PFD did not reflect the coupled status although the AP was, in fact, coupled to the selected flight guidance and the coupled light was illuminated on the ACP.

The third AFDS combination was the FD only (combination 3 from Table 3.1 and Figure 5.12). This mode was reasonably straight forward because the AP was not engaged and the AFDS was providing manual steering guidance only. The pilot was flying the airplane with no assistance from the AP and could follow the guidance of the FD bars. As well, the PFD and the ACP were consistent in that neither display showed a coupled indication, which made it easier to interpret.

The fourth AFDS combination included both the AP and the FD in an uncoupled state (combination 3 from Table 3.1 and Figure 5.13). This mode also maintained consistency between the pilots' PFD and the ACP. The trend, however, was one in which the absence of the coupled bar sometimes correctly indicated an uncoupled AFDS state (combination 1 and 3 from Table 3.1) while at other times the absence of the coupled bar was meaningless and the AFDS was, in fact, coupled (combination 2 from Table 3.1). The only way to be sure was to check the ACP, which meant the pilot had to look to the side and backwards to read the display. This was a poor human factors design as it is never good for the pilot to look down and backwards while flying, especially in Instrument Meteorological Conditions, as the pilot can become prone to disorientation.



*Figure 5.11.* CP140 EFDI showing the AP engaged and coupled.

In this screen capture, the AP is engaged and coupled to the TACAN lateral guidance mode and the Altitude Hold vertical guidance mode. The AP is therefore steering the aircraft toward the TCN station, even though there is no couple bar. This is understood by the combination of an outer loop mode (TCN) with no FD cueing; which together indicates that the AP is coupled.



*Figure 5.12.* CP140 EFDI showing FD only.

In this screen capture, the autopilot is not engaged. When outer loop modes such as the TCN and altitude hold modes are selected without the AP, the flight director bars appear and provide steering guidance for the pilot to follow.





*Figure 5.13.* CP140 EFDI showing both the AP and FD in an uncoupled state.

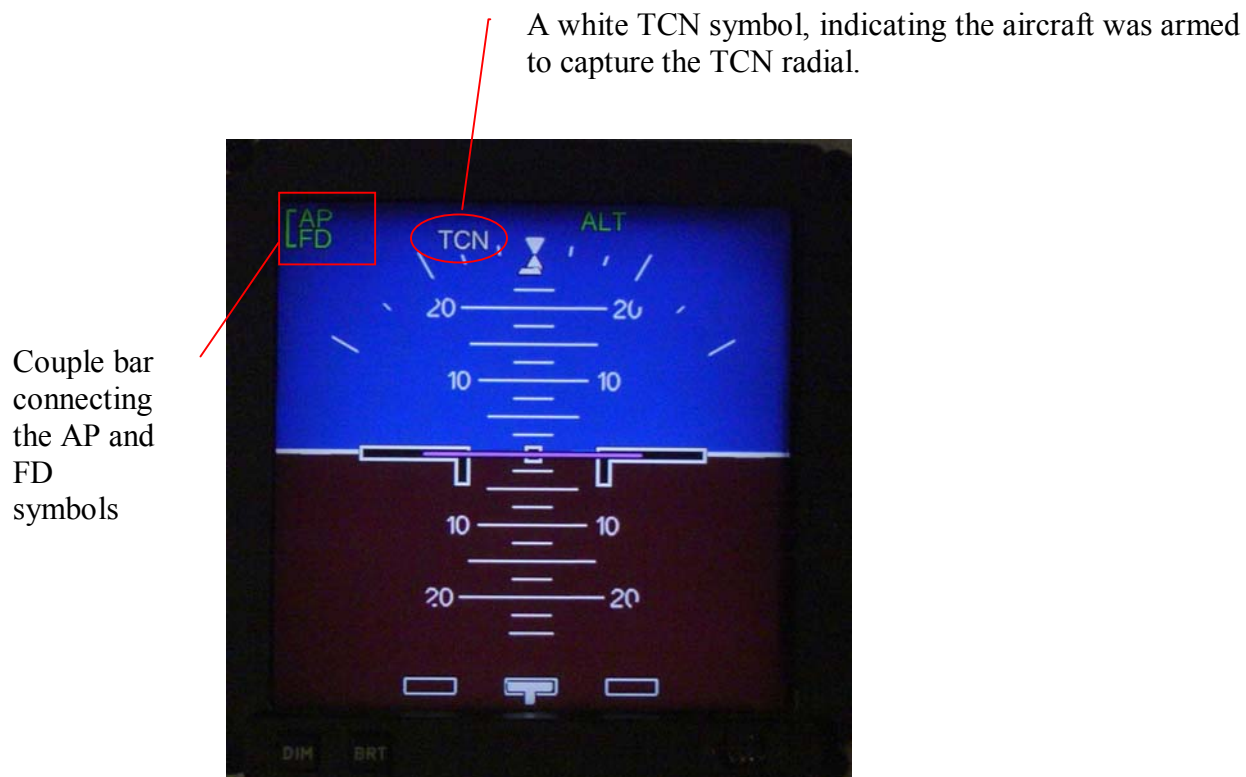
In this screen capture, the AP is engaged but not coupled to the flight guidance, indicated by the absence of a couple bar linking the AP and FD symbols. The magenta flight director bars provide manual steering guidance to the TCN station (lateral mode) and to a defined altitude (vertical mode), but the AP will not command the aircraft to follow.

The final combination had the autopilot engaged and coupled, in addition to the flight director being on (combination 5 from Table 3.1 and Figure 5.14). Again there was consistency between the pilot's PFD and the ACP.

What was problematic in all these cases was that it was impossible to rely solely on the pilot's PFD to determine the true modal state of the aircraft. Further, the true coupled state of the AFDS was not always represented by a coupled bar on the EFDI and this inconsistency in the display format created confusion for the pilot. The pilot was forced to go through a series of cognitive processes, such as "If, then" statements to determine the actual modal state of the AFDS. Even with the high level of automation in advanced cockpits, there is strong consensus that the pilot will continue to be ultimately responsible for the safe operation of the aircraft (Billings, 1991). As such, it is essential that the pilot be provided with the truth state of the aircraft and be given salient cueing following any mode changes to assist the pilot in making sound decisions.

Another problem the test pilots discovered with the display format of the AP was the lack of anticipation cueing. Because the current design made it difficult to determine the active mode of the AP system, it became even more difficult to anticipate what the aircraft would do next. When the pilot's expectations do not match reality, automation surprises will occur.

An additional problem with the display format of the AP was that the annunciations on the pilot's PFD were always the same green colour (when in the active state), regardless of whether it was the autopilot or the flight director that was engaged and regardless of whether the autopilot was coupled or uncoupled. Furthermore, regardless of the mode, the annunciations always illuminated in the same location. The



*Figure 5.14.* CP140 EFDI showing both AP and FD in a coupled state.

In this screen capture, the AP is engaged and coupled to the flight guidance as shown by the green couple bar. The FD is also present which increases the pilot's situational awareness by providing the steering guidance the AP is following.

effect was that it was very difficult, at a glance of the pilot's PFD, to quickly and accurately determine the modal status of the AFDS. Furthermore, the AP coupled bar on the AFDS was quite small and because the remaining indications were all so similar, the disappearance of the coupled bar from the pilot's primary flight display was difficult for the pilot to notice without directly looking for it. Recall the observation that "People simply do not easily notice the absence of things" (Wickens et al., p. 122).

The combination of these problems, or cause factors, could facilitate the occurrence of human errors and could easily result in an accident, as happened near Bangalore, in southern India, in 1990 (Flight Safety Foundation, 1990). In this Airbus A320 accident, both the pilots believed they were in one mode when in fact they were in another. The lack of awareness of the correct modal state cost them their lives as well as those of 90 others on board the aircraft. This accident demonstrates the critical importance of knowing what your aircraft is doing and what it will do next. For this reason, it is essential that each and every mode be clearly and unambiguously presented to the flight deck crews.

### *Recommendation*

The display format to communicate the coupled and uncoupled modal states of the AP should be redesigned. Attempting to implement a standard operating procedure to overcome this shortcoming will only result in extraneous communications and make an already confusing situation more complicated. A new design should incorporate the following human factors principles:

1. Indications of a coupled or uncoupled state should be *consistently* displayed on the pilot's primary flight display throughout all possible modal combinations.
2. The display should provide *anticipation cueing*. The pilot should be able to easily discern the projected flight path before the aircraft actually flies it.
3. The primary flight display should always present *truth data*. The pilot should not have to surmise what various combinations mean to determine the correct mode. Nor should the pilot have to look at multiple locations within the cockpit to determine the 'true' modal state. The current autoflight status should be clearly presented in a single flight management area on the primary flight display.

These modifications should be developed in consultation with pilots using a human centered design philosophy. As discussed previously, when the modifications have been made, they should be flight tested by qualified test crews in an operationally representative environment to ensure they are intuitive and user friendly.

## Chapter 6 – Conclusions and Recommendations

### *Overview*

One of the primary goals of this paper was to demonstrate that deficiencies in system design could lead operators to make mistakes that would reduce the safety, efficiency or effectiveness of a system. What may have traditionally been classified as pilot or human error during an accident investigation might today be attributed to system design flaws. The application of human factors engineering during the design phase and the involvement of human factors experts at each step of the development process is critical to minimizing human error during the operational use of the system. Czaja and Nair (2006) argue the importance of early involvement of human factors specialists but also recognize there are many reasons why this often does not occur until the evaluation stage of the project.

The four deficiencies discussed in this paper were raised during the flight test evaluation stage of the NFIMP. A summary of the conclusions and recommendation for each of these deficiencies is provided below.

#### *Deficiency One – Autopilot and Flight Director (AFDS) Loss of signal*

### *Conclusions*

The feedback to the pilots of a loss of signal when the AFDS was engaged and coupled to a navigation source was unclear and created confusion. From the signals given, the pilot was unable to quickly and correctly interpret the information provided on the EFDI so as to effect the appropriate actions in a timely manner. Further, the feedback

was not always immediately perceived by the pilot, which compounded any problems created by the signals lack of clarity.

The test pilots identified several human factors problems associated with the annunciation of a loss of signal to the AFDS. These problems included ambiguous cues, poor use of colour logic, insufficient information during uncommanded mode changes and a lack of attention capture cueing. The NFIMP design provided limited information to the pilot to make timely decisions and to ensure adequate situational awareness. The outcome could result in a delayed response or in the event the cue was missed, no response at all. Possible consequences could include an ineffective instrument approach, an incursion out of protected airspace or even a collision into high terrain. The underlying cause factors for these potential errors were determined to be an inability to easily discern between different modal states (ambiguous information), misleading colour coding of the display element, a lack of salient information to the pilot during status changes and insufficient methods of alerting the pilot to reversionary modes.

### *Recommendations*

The operator machine interface between the EFDI and the AFDS reflecting the loss of signal of a navigation source should be redesigned. First, unique status indications should be implemented on the pilot's primary flight display for each autopilot mode or sub-mode, to ensure that no two modes could be confused. In addition, supplemental information should be included during status changes to allow the pilot to identify the correct reversionary mode. This would provide the pilot with excellent situational awareness and allow him to make the right decisions and take the appropriate actions.

Any additional information would need to be succinct but would provide the added benefit of distinguishing different modal states. Further, the colour schema should be re-examined. Given appropriate supplemental information, green would be an acceptable colour during certain status changes such as a station overflight. During reversionary modes, yellow would be a more suitable colour choice and during any failure modes, red would be the most appropriate colour. Finally, auditory cueing should be considered an indispensable component of any autopilot system, especially during degraded operations. Voice cueing and unique tones for autopilot use are standard features in the commercial aviation industry. The addition of an aural cueing system on the CP140 AP and FD system will provide the additional safeguards required for the demanding military operations required of this platform and ensure that a change in modal status is not missed by any of the flight deck occupants.

#### *Deficiency Two – Automatic Flight Control System (AFCS) Disengagement*

##### *Conclusions*

###### *Normal disengagements*

The flight deck indications of a normal autopilot disengagement were subtle and could be missed. The disappearance of a small AP display element was not easily noticed and therefore it was necessary for the aircrew to be directly focused on the EFDI to observe the autopilot disconnect annunciation. This was a poor design in an advanced cockpit where the pilot was responsible for monitoring multiple displays, operating multiple systems and simultaneously carrying out complex mission tasks.



Several human factors problems identified by the test pilots were intrinsic within this design. There was insufficient modal cueing for the pilot, a lack of attention capture cueing and a lack of sufficient information to the flight deck to ensure a high level of situational awareness for all crewmembers. It would be possible for one crewmember to disengage the AP without the other crewmembers noticing. The resulting gap in situational awareness could create confusion in the cockpit and foster different expectations of the pilot's intentions of the aircraft flight path. An inadvertent disconnect could leave both pilots unaware the AP was no longer in control and result in an accident, similar to the crash of an Eastern Airlines flight into the Florida everglades in 1972 (NTSB, 1972). The underlying cause factors for these potential situations were identified as a failure to recognize a normal disengagement of the AP (lack of cueing), a breakdown in flight deck communications and a loss of situational awareness.

#### *Non-normal disengagements*

The observed flight deck indications of a non-normal autopilot disengagement were incongruent with human factors principles and could lead to a misinterpretation of the correct AP state and confusion in the cockpit. Specifically, the same alerting mechanisms were used for both emergency and non-emergency situations. This design could promote a culture of complacency and could train pilots to ignore critical flight deck indications. Some of the issues were as follows: red flashing indications were used to alert pilots to non-emergency situations; the pilots were unable to discern between an emergency situation and one that was simply non-standard; and there was a distinct lack of aural cueing for this critical flight system.

The human factors issues identified were a misuse of alert cueing, negative training for the pilots, improper use of colour logic and a lack of appropriate aural cues. The result could be the misdiagnosis of a critical situation or a failure to respond quickly or appropriately to an emergency situation. The flight safety incident in which the CP140 Aurora crew almost descended into mountainous terrain (FSIS, 2005) is an example of how critical this could be. The potential accident cause factors innate in this design were identified as an inability to differentiate between critical and non-critical alerts and an incorrect use of colour coding for non-emergency alerts.

### *Recommendations*

#### *Normal disengagements*

The method of alerting the pilot and co-pilot to a normal AP disengagement should be redesigned. The primary recommendation, and one that has become the industry standard, is the addition of an auditory cueing system. Furthermore, the same alerting mechanism should not be used for multiple systems, as was the case with the AFCS and RAAWS warning lights. This will raise the situational awareness of all crewmembers, ensure inadvertent disengagements do not go unnoticed and enhance the overall safety of flight operations.

#### *Non-normal disengagements*

The methods used to alert the pilot and co-pilot to a non-normal disengagement should also be redesigned. First, a red flashing eyebrow light should not be used to alert the flight crew to non-emergency situations. Second, as stated above, the same warning system should not be used for multiple systems. Finally and most importantly, due to the

potentially critical nature of an AP disengagement, a distinctive auditory cueing system should be implemented on the CP140 aircraft.

### *Deficiency Three – Unselected Approach Guidance*

#### *Conclusions*

The ability of the NFIMP design to display approach guidance on a primary flight display that was not selected by either the pilot or co-pilot was deemed unacceptable. It is essential that in any design the pilot must either directly command the information to be displayed or, as a minimum, he should be clearly advised whenever new information is presented or altered. In the case where more than one source of guidance is shown, it must be clear what the primary or active guidance system is.

Providing multiple sources of guidance to the pilot on a single display without distinguishing the primary or selected guidance would be a source of confusion and ambiguity. From a human factors perspective, this design lacked the fundamental principle of pilot involvement. As well, it was considered to be a catalyst for negative training by conditioning the pilots to ignore flight guidance information on their primary flight displays. It also increased display clutter and pilot cognition by requiring the pilots to dissect the information on the screen to determine what information to follow and what to ignore. This design could result in the pilot trying to fly an invalid approach or to fly an approach for which he was not cleared. The display of unselected approach guidance could lead to a lack of situational awareness on the flight deck, contribute to confusion in

the cockpit during a critical phase of flight, increase the pilot's cognitive workload and lead to an increase in pilot error.

### *Recommendations*

The NFIMP prototype requires modification to inhibit the display of unselected approach guidance to the pilot's primary flight display. There are multiple ways of accomplishing this task. The Fokker 28 facilitates this capability through the swapping of displays while the Challenger 604 permits the aircraft to transition directly from FMS guidance onto a traditional approach guidance signal, such as an ILS. Whatever option is decided upon, it is clear that some form of re-design of the system is required. It should only be possible to display one set of approach guidance to the pilot at a time. Any new design should use a human-centered philosophy to ensure that the pilot is the focal point of the model.

### *Deficiency Four – Coupled versus Uncoupled status of the Autopilot and Flight Director System (AFDS)*

#### *Conclusions*

The operator-machine interface between the pilot and the EFDI lacked appropriate and salient cueing to clearly communicate the true modal status of the AP. The inability of the pilots to correctly identify the AP mode with reference to the primary flight displays was unacceptable.

The human factors issues related to this deficiency were the provision of ambiguous information, a lack of clear indicators of the true modal state of the aircraft,

inconsistent display formats and insufficient salient data to enable the pilot to make sound decisions in a timely manner. The implication was that a comprehensive understanding of the AP system was required to interpret the various display combinations. The effect during testing was a higher level of cognitive activity to grasp what should have been a very intuitive and simple to understand annunciation of the current mode. The ramification was that the test pilots were often incorrect when describing expectant AP behaviour. Potential repercussions could range from a lack of situational awareness to complete confusion in the cockpit and could culminate in a flight safety incident or accident, similar to the 1990 crash of an A320 aircraft near Bangalore, India (Flight Safety Foundation, 1990) where both pilots believed they were in one mode when in fact they were in another. One of the underlying cause factors in such an accident would be the inability of the pilot to quickly and accurately determine the true modal status of the aircraft by referencing his primary flight display.

### *Recommendations*

The operator-machine interface to communicate the coupled and uncoupled status of the AP should be redesigned. There are many ways to effect the desired changes so long as human factors considerations are integral in any new design proposal. Any of the new Boeing or Airbus products would be suitable examples of acceptable display interfaces for autopilot systems that are employed all around the world. Any new design should consistently display all modal annunciations, provide anticipation cueing and present truth data on the primary flight display. The outcome of such a display change will be an overall improvement for the safety and efficiency of the flight operations.

*Summary*

Four deficiencies were identified in this paper along with the fundamental human factors issues that led to those deficiencies. A direct correlation was established to show the link between a flaw in the design of a system and the potential for an in-flight incident or accident, or as a minimum a reduction in mission efficiency and effectiveness. The underlying cause factors were presented to illustrate that these deficiencies could create the appropriate environment that would lead to what has historically been referred to as pilot error. Follow-on recommendations were then submitted to offer alternatives to the prototype design. This is, however, only the first stage in any redesign effort. What is critical now is that this paper becomes a catalyst for action and change. The next step in the process depends on the funding, support of the sponsor and willingness of the contractor to accept and implement the recommendations. Doing so will result in a more effective, safer and easier to use product for the end user: the operational line pilot.

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