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INSTALLING A NIGHT VISION IMAGING SYSTEM IN THE CF-188 HORNET: COMPATIBILITY OF WARNING AND CAUTION LIGHTS

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

Andrew John Soundy
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DEDICATION

This thesis is dedicated to my wife,

Melanie Lynn McCabe-Soundy,

and daughter,

Morgan Paige Soundy.

Without their support, understanding, and love the writing of this paper would not have been possible.

ACKNOWLEDGMENTS

I wish to thank all those who have helped me complete my Masters of Science degree in Aviation Systems. I would like to thank the faculty of the University of Tennessee Space Institute Aviation Systems Department, past and present, who have helped and guided me through this course of study. In particular I would like to acknowledge the support of the distance learning coordinator, Betsy Harbin, for her administrative assistance throughout the entire program.

I would also like to thank the Canadian Forces and the Canadian Department of National Defence for granting me permission to use project data to support the writing of this thesis and thus making its completion possible.

ABSTRACT

The purpose of this thesis was to investigate the NVIS compatibility of fire warning lights as installed during a NVIS upgrade of the CF-188 Hornet for operation with Generation 3 AN/AVS-9 night vision goggles. Data was gathered and compared to the specifications listed in MIL-STD-3009 to determine suitability of the implemented design. Of particular concern during the execution of this project was the compatibility of fire warning lights for operation in both day-time and night-time conditions with respect to NVIS radiance. The initial design placed the NVIS radiance of cockpit warning lights at a level commensurate with that suggested by MIL-STD-3009. During the evaluation, significant concern arose regarding the radiance of the proposed warning light configuration. The problems were significant enough that the final design version incorporated fire warning lights with a NVIS radiance value approximately seventy times greater than the value suggested by MIL-STD-3009. It was found that the conflicting demands of day versus night operating conditions rendered the initial fire warning light design ineffective. Through the investigation conducted during the evaluation, this study concludes that, for single seat, canopy covered cockpit, fighter type aircraft employing Generation 3, class B, Type I NVIS devices, using a higher NVIS radiance value than that set out in MIL-STD-3009 for warning lights will not adversely affect completion of the mission. Moreover, it is further concluded that using this approach is a satisfactory means by which to address many of the conflicting design requirements for NVIS compatible cockpits in order to ensure safety of flight and mission effectiveness. This study also recommends, with due consideration given to the level of detail at which the

evaluation it is based on was conducted, an approximate optimum value for the NVIS radiance of cockpit warning lights that ensures effective function of the light with minimum impact on employment of the NVIS device.

As a result of this work and the associated findings concerning the NVIS radiance levels of the cockpit warning lights, a satisfactory design was implemented that met safety of flight requirements permitting the system to proceed on to operational testing to determine mission suitability.

PREFACE

The work presented in this thesis is based in part on an evaluation conducted at the Canadian Forces Aerospace Engineering Test Establishment, CFB Cold Lake, AB in support of a Government of Canada Department of National Defence capital project. Permission has been granted by the Department of National Defence to use the work conducted for this project as a foundation for the paper.

This paper was written by a student attending the University of Tennessee Space Institute in fulfillment of one of the requirements of the Aviation Systems Course of Studies. The paper is a scholastic document, and thus contains facts and opinions which the author alone considered appropriate and correct for the subject. It does not necessarily reflect the policy or the opinion of any agency, including the Government of Canada and the Canadian Department of National Defence.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AA	Air-to-air
AETE	Aerospace Engineering Test Establishment
AG	Air-to-ground
AGC	Automatic gain control
AGL	Above ground level
ALR-67	CF-188 radar warning receiver
AN/AVS	Airborne visual search equipment
AOA	Angle of attack
APU	Auxiliary power unit
arcmin	Arc minute (one 60^{th} of an angular degree)
BATT SW	Battery switch
BRT	Bright
DoD	Department of Defense
DT&E	Developmental test and evaluation
EFP	Experimental Flight Permit
EM	Electromagnetic
ET&E	Engineering test and evaluation
FOV	Field of view
grams	Grams mass
HUD	Heads up display
IIT	Image intensifier tube
INST PNL	Instrument panel
IR	Infra-red
LANTIRN	Low Altitude Navigation and Targeting Infrared for Night
LED	Light emitting diode
LOS	Line of sight
MC	Master Caution
MCP	Micro-channel plate
MIL-STD	U.S. military standards
NVG	Night vision goggle
NVIS	Night vision imaging system
OT&E	Operational test and evaluation
QTY	Quantity
RadAlt	Radar altimeter
U.S.	United States
UFC	Up front control
VA	Visual Acuity

Symbols

cd	Candela
cm	Centi-meters
cy/mr	Cycles per mili-radian
fc	Foot Candles
fL	Foot Lambert
ft	Feet
G	Gain
g	The Earth's gravitational acceleration
$G(\lambda)_A$	Spectral response function of class A NVIS devices
$G(\lambda)_B$	Spectral response function of class B NVIS devices
m	Meters
mA	Mili-amp
mLux	Mili-Lux
mm	Mili-meters
$N(\lambda)$	Spectral radiance function of a cockpit light source
nm	Nano-meters
NM	Nautical Mile
nNR_A	Nano NVIS radiance for Class A NVIS devices
nNR_B	Nano NVIS radiance for Class B NVIS devices
^{o} C	Degrees Celsius
sec	Second
W	Watts
δ	Number of secondary electrons emitted in a MCP tube
λ	Wavelength

CHAPTER I

INTRODUCTION AND BACKGROUND INFORMATION

Antecedents

General

The conduct of aerial warfare has changed dramatically over the past few years. The nature of the threat to friendly combat aircraft has changed, as has as the types of missions that modern coalition combat aircraft must conduct. Since the fall of the Berlin wall in 1989 the threat to the modern fighter aircraft has morphed from the complex form of sophisticated electronically guided weapons that characterized the Cold War, to predominately visually guided hand operated systems that can be as simple as a small assault rifle. In the same fashion, the modern combat mission has changed as well. Instead of flying overt missions against large, readily identifiable pieces of military hardware on open battlefields, coalition pilots are now being asked to strike targets comprised of non-military equipment that is often located within complex civilian urban areas.

To survive against this emerging threat, coalition air forces are relying increasingly on avoidance tactics. Rather than depending solely on complicated electronic counter measures techniques, today's combat pilot is operating increasingly under the cover of darkness. By conducting operations at night, the enemy's task of employing visually guided weapons is severely complicated; however, the same complications that create difficulties for the enemy also create problems for friendly forces in the conduct of their own mission.

Aids to Night Operations

The greatest concern of aircrews operating fast moving aircraft at night is the high potential for collision. The concern over collision is multi-faceted. Collision can occur between the aircraft and the ground or an object on the ground, between the aircraft and another friendly aircraft, or between the aircraft and an enemy aircraft. Other concerns focus on effectively conducting the mission in a night environment and finding a means of accurately acquiring targets in the dark.

There have been several approaches to enabling safe and effective operations in a night environment. Many of these approaches have focused on advanced electronic mechanisms designed to reduce pilot workload at night and handle many tasks with no input required from the pilot at all. Indeed, many of these devices enable the accomplishment of tasks that an unaided human pilot would not be capable of at night. For instance the LANTIRN system, shown in Figure 1, is employed on many modern fighters and is cable of flying the aircraft on which it is installed as low as 200 ft above terrain, at night, with no input required from the pilot (Airforce Technology, 2006). However, although these systems are very capable, they have several major drawbacks: they are very expensive to purchase[1], require significant investment in personnel training, and are susceptible to failures which can strain maintenance organizations.

[1] Many sources quote the cost of the LANTIRN system (targeting pod and navigation pod) at well over four million U.S. dollars.

Figure 1. F-16 Equipped with LANTIRN

Source: United States Air Force, "Photos," *Air Force Link* [Official Website of the United States Air Force]; available from http://www.af.mil/shared/media/photodb/photos/010101-F-0101S-006.jpg; Internet; accessed 26 August 2006.

At the other end of the spectrum is the approach of simply doing nothing to aid the pilot at all. Indeed for many years, due to limitations in technology and scarcity of funding, this was really the only viable option. Unaided night tactics required aircrew to severely curtail the flexibility in tactics that they were able to enjoy during day-time operations. Since there was no dedicated means at night by which aircrew were able to ensure separation from other aircraft or the ground, they were forced to fly in formations that would ensure no such collisions could occur. By ensuring separation from other friendly aircraft either in altitude, by geographic separation, or a combination of both, the risk of aircraft-to-aircraft collision could be greatly reduced. A collision with the ground could be avoided in a similar fashion by studying the area to be flown over and limiting the minimum altitude at which operations would be conducted, thus providing a safety cushion. Maintaining awareness of the location of other friendly aircraft required the use of onboard sensors with the negative side effect of reducing the amount of time that these sensors could be used for their primary function of locating hostile units. Consequently, although the requirement existed to conduct operations under the cover of darkness, mission effectiveness during unaided operations at night was severely degraded when compared to equivalent day-time operations.

Another option for combat air operations at night became available in the 1980s and that was the employment of night vision imaging system (NVIS) devices. As will be detailed later in this paper, there are two types of NVIS devices as shown in Table 1.

By the 1980s, Type I night vision goggle (NVG) technology had progressed to the point where NVIS devices were small enough to be practical for use within the close confines of a fighter aircraft cockpit, and were effective enough to be useful in the conduct of night combat missions. Indeed "while the goggles do not turn night into day, they do open up the night considerably. Pilots can essentially fly day-time tactics at night." (Hehs, 1998). This new technology gave combat aircraft design and acquisition specialists new options. Although the advanced electronic devices mentioned earlier

Table 1. Types of NVIS Device

NVIS Device Type	**Description***
Type I	This device employs Generation 3 IITs and makes provision for direct viewing of the NVIS image on a phosphor screen, where the image is placed in direct LOS of the operator.
Type II	This device employs Generation 3 IITs and projects the NVIS image on a transparent medium, usually a HUD with appropriate symbology, placed in direct LOS of the operator.

*(U.S. Department of Defense, 2001, 4)

certainly still had a place in combat operations, NVGs provided a more general solution. For instance, LANTIRN had very specific application for use in the low altitude night strike role which, although important, had to be limited to a small percentage of available aircraft due to the high cost of the equipment. NVGs on the other hand offered a cheap, albeit more general, solution to previously limited options for night operations. The Canadian government recently purchased one set of AN/AVS-9 NVGs for each of its operational CF-188 Hornet fighter aircraft at a cost of $14,375.00 Canadian dollars for each pair (Canada,National Defence, 2005). This is a small fraction of the cost that would have been incurred had LANTIRN been purchased as an alternative. With a relatively minor outlay of capital acquisition funds, operators of combat aircraft are able to equip all their aircraft with a very capable night fighting system which, although quite general in application, will allow these aircraft to maintain viability well into the future.

Incorporating NVIS Devices

Unfortunately, equipping existing, and for that matter, even new aircraft for operations with NVIS devices is not just as simple as purchasing NVIS crew equipment and commencing operations at night. As will be shown, the light amplifying nature of NVIS devices, along with the AGC technology that they employ, prevents them from being used in an aircraft that employs conventional cockpit lighting equipment. An aircraft cockpit must be designed specifically for use with NVIS devices in order to ensure their effective employment. Cockpit design must focus on the technical compatibility of the NVIS device with the cockpit itself, exterior airframe influences such as external lighting, and appropriate provision for device stowage. Human factors issues must also be addressed to include spatial compatibility of the NVIS device with the cockpit environment, compatibility with crew escape systems, as well as crew interface with the various controls in the cockpit.

There are essentially two approaches that can be taken to ensuring the compatibility of modern combat aircraft cockpits with NVIS devices. Perhaps the simplest approach is to design the cockpit from the earliest stages of prototype manufacture to incorporate compatibility features. This ensures that NVIS operations become an integral part of the aircraft's design intention from the prototype phase on, providing seamless integration of NVIS devices throughout the lifetime of the aircraft.

The second approach is to create a design and modify an existing, non NVIS compatible cockpit, to be compatible with the device selected for use with that aircraft. This is perhaps the most prevalent approach that is being seen today. Due to the fact that NVIS technology has only recently enabled the use of such devices in small fighter sized cockpits, NVIS compatibility was not included in the original designs of many existing front line, coalition combat aircraft. With the technology now available, and with the cost of NVGs being comparatively lower than other imaging systems, many militaries around the world are modifying their existing aircraft to become NVIS compatible. These modifications involve many different facets as has already been alluded to. Of all these different considerations however, this thesis focuses on the human factors concerns surrounding the compatibility of cockpit lighting modifications with the use of NVIS devices.

Background

The Canadian Forces decided early in the millennium to modernize its fleet of CF-188 Hornets to extend the usefulness of the fleet well beyond 2015. Part of the modernization project involved the incorporation of the AN/AVS-9 NVGs for use by aircrew in the conduct of night combat missions. As discussed, incorporating NVGs for use by aircrew involves modifying the existing cockpit so that it becomes compatible with NVIS devices.

The modification was deemed necessary to extend the useful life of the aircraft and significantly expand its operational potential in all roles and missions. An initial investigation had been conducted in 1999 to research the feasibility of such a modification with several options being evaluated for possible inclusion. Armed with this data, the CF-188 project office developed an all encompassing modification design that included a new NVIS compatible cockpit lighting system, a cockpit stowage compartment, and an ejection seat modification to incorporate a video recording device for the scene as viewed by the pilot through the NVGs[2].

The test project was split into three phases (Canada. AETE, 2005b, 1). The first phase was a developmental test and evaluation (DT&E) phase designed to investigate the feasibility of the designed modification. If any obvious faults with individual components were discovered at this stage, the design could be modified to correct any discrepancies before moving on to the second phase. The second phase was an engineering test and evaluation (ET&E) phase designed to evaluate the complete system

[2] For a complete description of the cockpit modifications, refer to Appendix B

and its function as an integrated modification. Items such as specification compliance, human factors concerns, as well as safety-of-flight issues were investigated. The final phase was an operational test and evaluation (OT&E) phase to investigate the operational suitability of the modification for use in its intended mission.

Introduction

General

This study was based on the project carried out at the Aerospace Engineering Test Establishment (AETE) to modify the cockpit of the CF-188 for use with the AN/AVS-9 NVGs. This project was a significant undertaking for the organization and was carried out over several years. As such, to focus on the entire project within this paper would be beyond the scope of its intent and of an order of magnitude that would not permit the author to do it justice. Instead this paper focuses on one aspect of the CF-188 cockpit modification, namely the compatibility of the cockpit fire warning lights with the NVGs.

There has been much discussion on what the permissible radiance of NVIS compatible warning and caution signals should be. The main reference for such a specification is U.S. DoD MIL-STD-3009[3] which lays out compatibility standards for NVIS compatible cockpit lighting. MIL-STD-3009 is a U.S. military document containing specifications that are intended to provide a guideline for the compatibility of NVIS cockpits. “It is applicable to all systems, subsystems, component equipment, and hardware that provide the lighting environment on aircraft where NVIS are employed.”

[3] MIL-STD-3009 was derived from MIL-L-85762A to preserve the data contained in the latter when it was superseded in 2001. MIL-STSD-3009 maintains precisely the technical information that was contained in MIL-L-85762A. Please refer to the forward in MIL-STD-3009 for further explanation.

(U.S. DoD, 2001, 1). As such the document is general in its applicability and was not intended for any one particular aircraft.

The radiance discussion revolves around the trade-off between a particular warning light attracting the operator's attention, balanced with the potential degradation of the NVIS device and incumbent impact on the mission. Also factored into the discussion are the trade-offs that must be made between the warning and caution lights satisfying the demands of the NVIS environment as well as providing sufficient luminance for operation in daylight during day-time operations. All of these competing demands must be considered to derive a satisfactory design solution; they form the very crux of the problems that confront any NVIS cockpit designer. For the CF-188 modifications, the decision was made when the initial design was implemented to keep the radiance levels of the fire and auxiliary power unit (APU) warning lights at the level dictated by MIL-STD-3009. During the conduct of the CF-188 cockpit modification evaluation conducted at AETE, the test team highlighted the engine fire and APU fire warning lights as being unacceptably dim for safe function within the cockpit despite their compliance with the specification.

Thesis

Based on the findings of the project conducted at AETE, this study investigates the optimum radiance requirements for warning lights in a single seat, canopy covered cockpit, fighter type aircraft. In Table III of MIL-STD-3009 for warning and caution signals, it is stated that for class B, type I NVIS devices, there is a minimum NVIS radiance requirement (nNR_B) of 47 and a maximum of 140 (U.S. DoD, 2001, 14). This specification is ultimately only a guide and if the testing authority deems the item under evaluation to be acceptable, regardless of its specification compliance, there is no reason why it should not be fielded as such.

This study concludes that, for single seat, canopy covered cockpit, fighter type aircraft employing Generation 3, class B, Type I NVIS devices, using a higher NVIS radiance value than that set out in Table III of MIL-STD-3009 for warning and caution lights will not adversely affect completion of the mission. Moreover, it is further concluded that using this approach is a satisfactory means by which to address many of the conflicting design requirements for NVIS compatible cockpits in order to ensure safety of flight and mission effectiveness. This study also shows, with due consideration given to the level of detail at which the evaluation it is based on was conducted, an approximate optimum value for the NVIS radiance of cockpit warning lights that ensures effective function of the light with minimum impact on employment of the NVIS device.

It is intended that the work conducted and presented in this investigation will help provide support and empirical evidence concerning the NVIS radiance levels of cockpit warning lights, and that it might benefit future NVIS compatible cockpit designs.

Outline

The argument for this thesis is divided over four chapters. Firstly, to set the background for the technical discussion, it is necessary to describe the nature of class B, Type I NVIS devices. This chapter describes these devices and how they function. Particular emphasis is placed on how these devices intensify light and how the AGC feature operates. Details are highlighted of how internal cockpit lighting can interfere with the operation of these devices, causing a degradation of mission effectiveness. Also highlighted are the conflicting demands that are placed on the design for an NVIS compatible cockpit that must function during both day-time and night-time missions.

Secondly, the method of investigation for the cockpit warning lights is discussed. This chapter describes how the compatibility of the cockpit warning lights with the NVGs was assessed, the type of data that was collected, and how this allowed support of the thesis described above.

Thirdly, the results of the investigation are presented. The results are discussed in terms of the thesis presented above. The results obtained in this investigation include some quantitative measurement but are concerned mostly with comments and opinion obtained by the test pilots and flight test engineers that comprised the test team. The discussion makes argument for the NVIS radiance level of the final warning light design that was incorporated.

Finally, the material presented is summarized and concluded upon to support the argument presented in the thesis statement. Where appropriate, recommendations are made, as well as potential caveats to the evidence presented. Potential follow on research is also suggested that might further the investigation.

CHAPTER II

NIGHT VISION IMAGING SYSTEM THEORY

Light intensification theory is straight forward in its approach. NVIS systems operate by simply intensifying the existing ambient or reflected light so that it becomes visible to the human eye. It is important to note that there must *some* light energy present in order for NVIS systems to operate. An environment that is in complete darkness will not permit these devices to work. This chapter will take a brief look at existing NVIS technology and in particular the theory that enables the AN/ANVS-9 NVG to operate. Most importantly, the section will discuss in some detail the problems that NVIS devices can encounter in their employment and how these problems impact the design of an NVIS compatible aircraft cockpit. Indeed the entire aim of designing an NVIS compatible cockpit is to minimize or eliminate completely the undesirable characteristics that must be dealt with when employing NVIS devices.

This chapter will also examine the relevant sections of MIL-STD-3009 and take a look at the origin and thoughts behind some of the specifications contained therein. It is important to understand the origin of the specification when considering its application for a particular project. Depending on how the specification values are obtained, they either may, or may not be relevant to the project for which their use is being contemplated.

Light Intensification Theory

General

Light intensification technology for combat aviation has been in existence since the 1940s. The first devices conceived at that time have come to be known as Generation 0 devices. They relied on an external, covert light source to illuminate the object under observation. The illuminator employed an infra-red (IR) filter to hide the illuminating energy from observation and detection by the naked eye. Since that time, NVIS devices have evolved through four generations with the latest Generation 4 NVGs requiring only natural ambient external illumination and providing image intensification at levels three times higher than their Generation 3 predecessors (Hehs, 1998).

This section will cover only Generation 3 NVGs, the family of which AN/AVS-9 NVGs are a member of.

Micro-channel Plate Technology

Generation 3 NVGs employ image intensifier tubes (IIT) which accomplish the task of intensifying the ambient or reflected light. Figure 2 shows the basic composition of a Generation 3 IIT. Light enters the IIT through the objective lens and is focused onto a photocathode. When the photons of light strike the photocathode each point on the cathode emits a stream of electrons in a quantity that is proportional to the degree to which the point has been illuminated by the image being viewed. The emitted electrons then enter the front of the micro-channel plate (MCP). After passing through the MCP, the intensified flow of electrons strike a monochromatic phosphor screen. The greater the number of electrons striking the screen, the brighter the reaction of the phosphor and thus

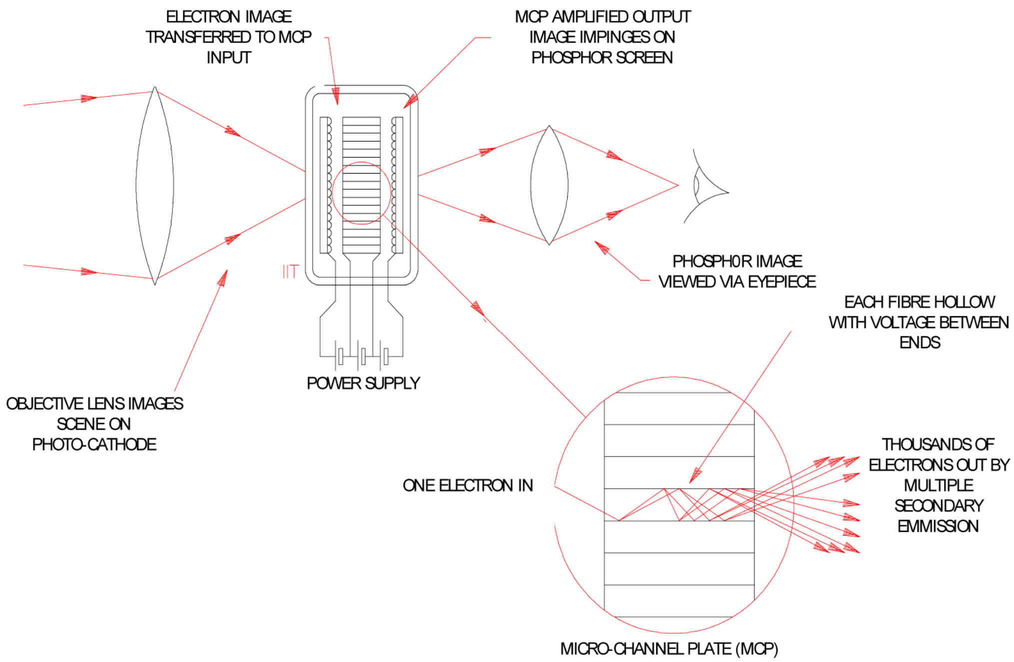

Figure 2. Scematic Diagram of a Typical Generation 3 IIT

Source: Bentham Instruments Ltd, *NVIS Compatibility (A Primer)*, issue 2.01. (Reading, England: Bentham Instruments Ltd., 1997), 3.

an intensified image of the objective scene is produced (Bentham Instruments Ltd, 1997, 3).

The actual light intensification process in the IIT occurs by way of the MCP. A close up schematic of a generic MCP is shown in Figure 3. The MCP consists of a flat disc that is composed of many fine, extruded tubes that are coated on the inside with a semiconductor layer. In order to function correctly, a source of voltage must be applied across the MCP. As an initial incident electron enters an individual MCP tube and strikes the wall, δ secondary electrons are emitted[4]. In the next stage δ^2 electrons are emitted,

[4] δ is the symbol used to represent the number of secondary electrons emitted. In the case of Figure 3, δ is equal to 2.

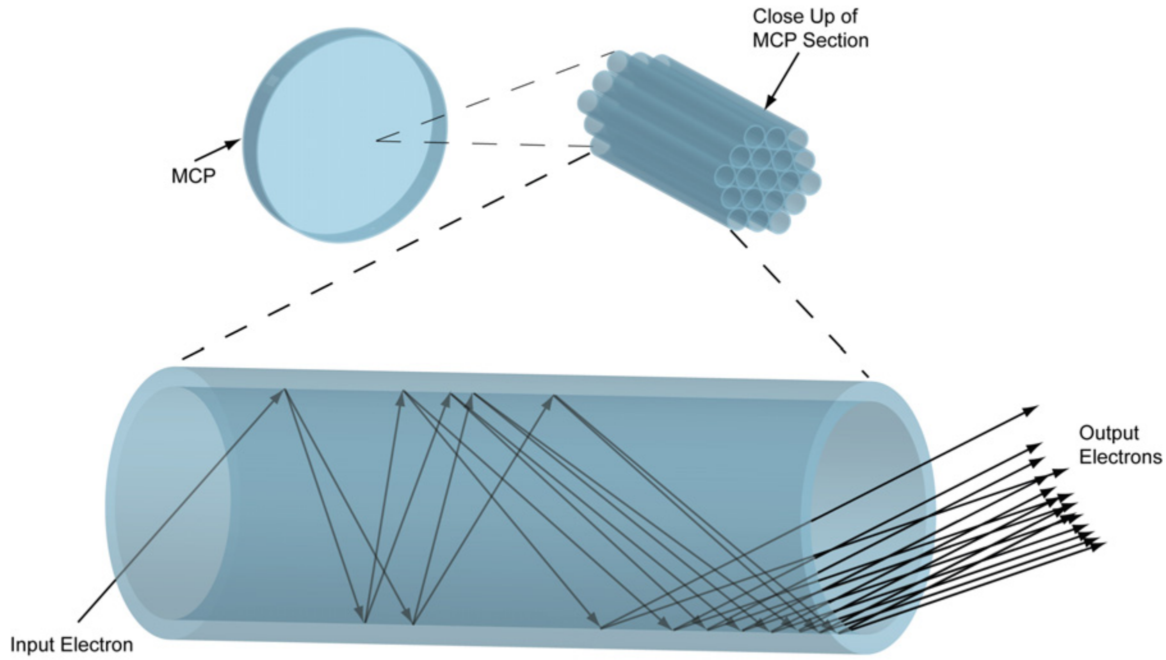

Figure 3. Generic MCP Schematic and Operation

and so on for a total gain of $G = \delta^n$ where n is the total number of stages[5]. The total number of stages is dependant on the tube length to diameter ratio (Wiza, 1979, 588). As can be seen, the material that the MCP is constructed of produces extra electrons in proportion to the number of incident electrons. Since the number of incident electrons is proportional to the illumination level of the objective scene, the image that is produced on the phosphor screen is thus a depiction of the objective scene at an increased intensity portrayed at a high enough level so that it can be viewed by the human eye. A picture of the AN/AVS-9 NVGs and a typical NVG intensified image as seen through the goggles can be found in Appendix A.

[5] In the case of Figure 3, n is equal to 4. G represents the relative gain of the electron stream.

Automatic Gain Control

To avoid damaging the IIT and to maintain an image with sufficient contrast detail, Generation 3 NVIS devices employ an automatic gain control (AGC). NVIS devices are extremely sensitive pieces of equipment that are designed to respond to very low light levels on the order of 0.001 cd/m^2.[6] Of course if the NVIS device is exposed to light levels that are significantly brighter than that, there can be two undesirable effects. Firstly, since the objective scene in this case is so bright, the device will intensify every part of the scene to the maximum level of the phosphor viewing screen. The end result is that the image would simply appear as a uniformly bright disc with no image contrast. Secondly, a very bright objective scene would draw excessive current through the circuitry supplying power to the MCP, potentially damaging the device.

The AGC serves to mitigate these two undesirable effects in the following way. By sensing the current draw across the MCP, the AGC is designed to reduce the voltage, and hence gain of the MCP should the current rise to a predetermined threshold. This prevents the current from getting to a level where damage may occur and also keeps the image levels from saturating thus ensuring sufficient contrast in the displayed image such that the user is able to discern the scene (Bentham Instruments Ltd, 1997, 6). However, as shall be seen later in this chapter, the AGC can also lead to incompatibility issues if the NVIS device is operated in an incorrectly designed NVIS cockpit.

[6] cd/m^2 is the standard unit of luminance defined as candela per meter squared. It represents luminous intensity over a given area.

Classification of NVIS Devices

General

NVIS devices have been designed to work in many different environments. They have taken on two generic forms each of which can be allocated to any one of three different classes. This section will briefly discuss the different types and classes of NVIS device to situate the AN/AVS-9 NVGs within the spectrum of available NVIS equipment.

Types of NVIS Device

There are two types of NVIS device as previously detailed in Table 1. These types were developed so that NVIS devices could be adapted to suit the needs of different cockpit environments. Additionally, the type of device determines its complexity and subsequently its cost to manufacture. The AN/AVS-9 NVIS device is a type I device. The device places an individual IIT approximately one inch in front of each of the user's eyes with the image displayed on a phosphor screen that is located within the IIT. For a complete description of the AN/AVS-9 NVG, see Appendix A.

Classes of NVIS Device

NVIS devices were designed to operate predominately in the IR region of the electromagnetic spectrum. This allows them to remain sensitive to IR energy that is retained by objects on the surface of the earth long after the sun has fallen below the horizon.

There are three classes of NVIS device, namely class A, B, and C. The distinction between each class is made on the basis of their spectral response. A graphical representation is shown in Figure 4.

The earliest NVIS devices were predominately class A. As can be seen, class A NVGs maintain a greater than 1% response all the way down to a wavelength of almost 625 nm. By referring to the portion of the electromagnetic (EM) spectrum depicted in Figure 5, insight can be gained into how class A NVGs respond to EM energy between 450 nano-meters (nm) and 950 nm wavelength. While class A NVGs certainly maintain the greatest part of their response in the IR region above 700 nm, they also respond to red and orange colored visible light.

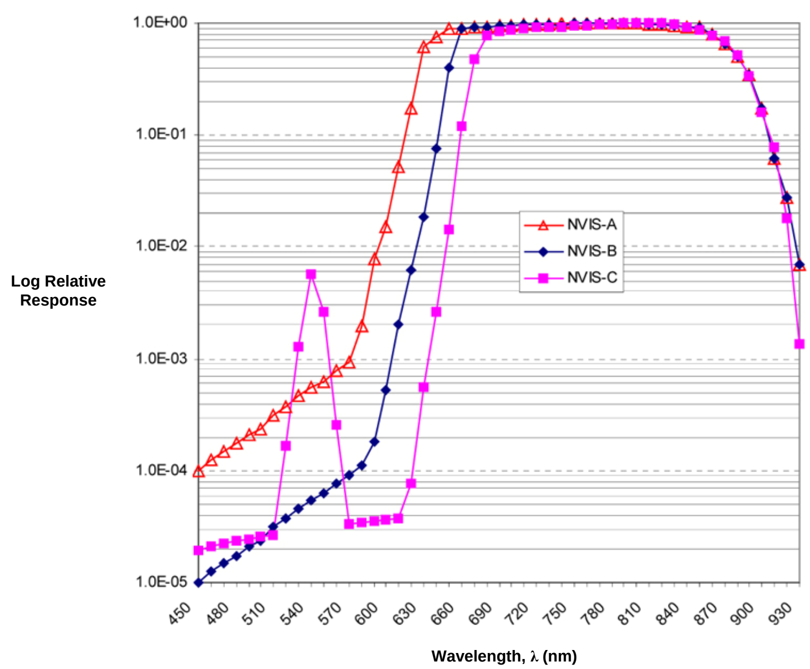

Figure 4. Wavelength Response Curves for Class A, B, and C NVIS Devices

Source: U.S. Department of Defense. *Department of Defense Interface Standard MIL-STD-3009: Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible*. (Wright-Patterson AFB, OH, 2001), 7.

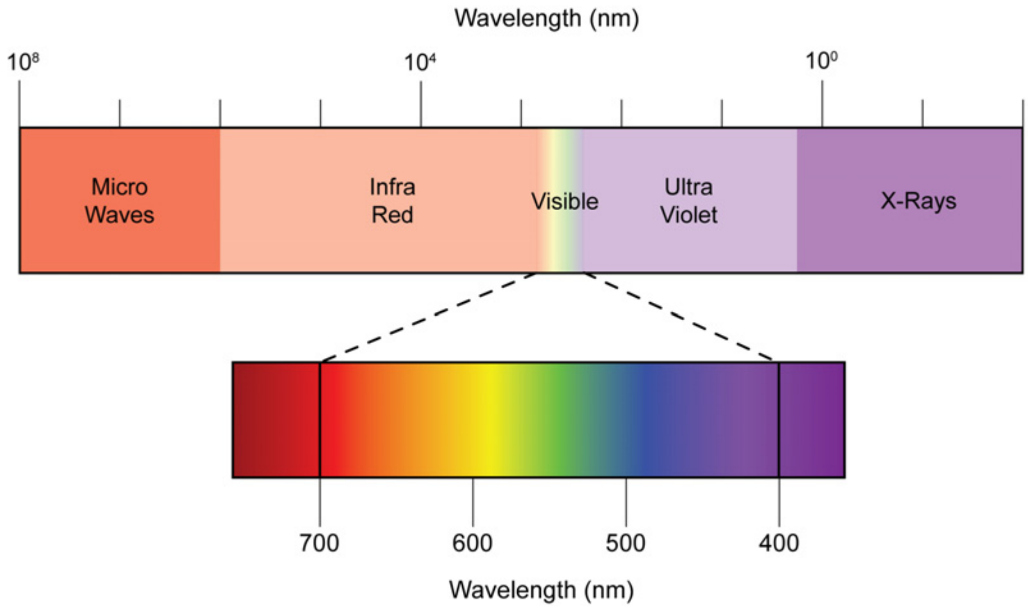

Figure 5. A Portion of the EM Spectrum

As will be seen in the next section, this has implications for the use of red light in aircraft cockpits where NVIS devices are to be used.

Class B NVGs are an improvement over class A NVGs. Class B NVGs cut off in response at approximately 665 nm. This means that class B devices do not respond to certain shades of visible red light with shorter wavelengths such as orange. All but the deeper shades of red fail to elicit a response from the devices and thus, if careful consideration is given to the shade of red lighting used in the cockpit, compatibility issues for red lights can be minimized.

Class C NVIS devices are the newest devices to have been developed. They improve on class B devices by cutting off at even higher wavelengths (approximately 675 nm) thus avoiding response to an even greater palette of red shades which can therefore be made available to designers. These devices also employ a further enhancement affectionately referred to as the “green leak”. This is a feature where a band pass filter has been included at a wavelength of approximately 550 nm which Figure 5 indicates is at the wavelength of visible green light. This was born of the necessity to view HUD images through Type I NVGs. Since heads up display (HUD) images are focused at infinity, and since by design they are situated directly in front of the pilot’s line of sight (LOS) it is necessary to be able to view the image through the Type I NVIS device being used without having to operate the HUD at a very high intensity setting. By providing a partial “leak” to visible green light (which HUD devices generally employ) this becomes possible whilst at the same time maintaining negligible response to other colors of visible light within the cockpit.

With reference to the specification laid out in MIL-STD-3009, class C NVIS devices are not specifically mentioned. Instead, direction is given to treat these devices in accordance with the specification for class B devices since compatibility with class B will ensure compatibility with class C (U.S. DoD, 2001, 2).

NVIS Compatibility Issues

General

Now that general NVG theory of operation and device classification has been discussed, the information will be used to describe some of the compatibility issues that can be faced when trying to employ these devices in aircraft cockpits. It is these issues that cockpit design teams must consider when creating NVIS compatible cockpits to ensure the most effective employment opportunity for NVG equipped aircrews.

Compatibility issues are generally a result of "the extreme disparity between the luminance of the out-front scene (maybe 0.001 cd/m^2) and the luminance of displays and controls (maybe 2 cd/m^2)" (Bentham Instruments, 2001, 6). Because the luminance of the cockpit displays is so much greater than that of the external scene it can become the dominant stimulus for the NVIS device.

Canopy Reflections

Canopy reflections become a concern when the energy emitted by the cockpit displays is reflected in the aircraft canopy. As has been detailed, the energy emitted by the cockpit displays is generally three orders of magnitude greater than that of starlight reflected from foliage. If the reflected energy in the aircraft canopy is situated between the objective lens of the NVG and the scene being observed, it will become the dominant feature of the NVG image completely obliterating the intended viewing scene outside of the aircraft. This of course will completely negate the effectiveness of the NVGs.

Reduced Image Contrast

The concern over reduced image contrast arises as a result of undesired operation of the AGC. As previously described, the purpose of the AGC function is to reduce the gain of the IIT when the scene being viewed is reflecting light at high illumination levels. Reducing the gain of the IIT prevents the phosphor screen image from saturating. Compatibility issues arise when cockpit lights that can be in the region of three orders of magnitude higher in intensity than light reflected from the observed scene cause the AGC function to be invoked. While the response of the AGC is appropriate for the illumination level of the cockpit lighting, it is not appropriate for that of the observed scene. Consequently, the gain is reduced to such a low level that all scene contrast is lost thus negating any effectiveness of the NVIS device. An example of this effect is shown in Figure 6.

Although in this example the AGC has been invoked by a high illumination source exterior to the cockpit (the setting sun) the impact is the same were the source to have been in the cockpit itself. As can be seen, all contrast in the terrain at the bottom of the field-of-view (FOV) has been lost due to the high level illumination source invoking the AGC and lowering the gain of the NVG. Instead of the usual detail being displayed in the terrain layer, it simply appears as a black band without any contrast being shown. There is obviously no way that the operator could discern any information on the ground thus preventing any chance of locating objects of interest or enemy activity. In the case of an external light source the situation can be improved by moving the light source outside of the NVG FOV. For internal lighting contamination this would not be possible since there is no way to move away from the high illumination source.

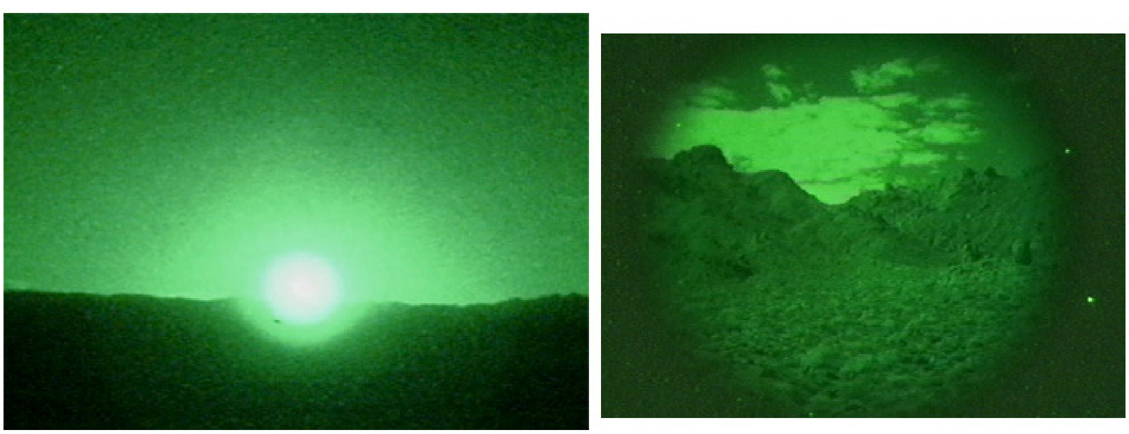

Figure 6. NVG Image With and Without AGC Activated

Reduced Covertness

As detailed in chapter I, combat aircraft operating with NVIS devices are doing so to employ the cover of darkness in order to remain covert in their operations and avoid detection by the enemy. If cockpit lighting is producing illumination levels that are high enough to permit detection by the enemy, it will prevent any chance of remaining undetected (Bentham Instruments, 1997, 7).

Minimizing Aircraft Cockpit Lighting Compatibility Issues

The design of NVIS devices has evolved to try and address the compatibility issues described above. As shown in Figure 7, the approach revolves around separating the EM spectrum into two sections (the cockpit lighting section and the NVG section) and implementing filters in the cockpit lights and NVIS device to mutually exclude each component from operation in the other's allocated bandwidth as much as possible to prevent contamination.

As previously described, in the case of class B and C NVIS devices, a coating is applied to the objective lens that cuts off response of the NVGs at 665 nm and 675 nm respectively. This essentially means that the devices will not respond to energy at wavelengths shorter than those values. This of course means that any light below those wavelengths will not present an issue if it is reflected in the canopy and also will not cause the AGC to invoke since the NVGs are not responsive to the energy. Therefore, as long as the wavelength of light within the cockpit can be kept shorter than the NVG filter values, there should be no compatibility issues. For a number of reasons however, the practicality of this is not as simple as it would appear.

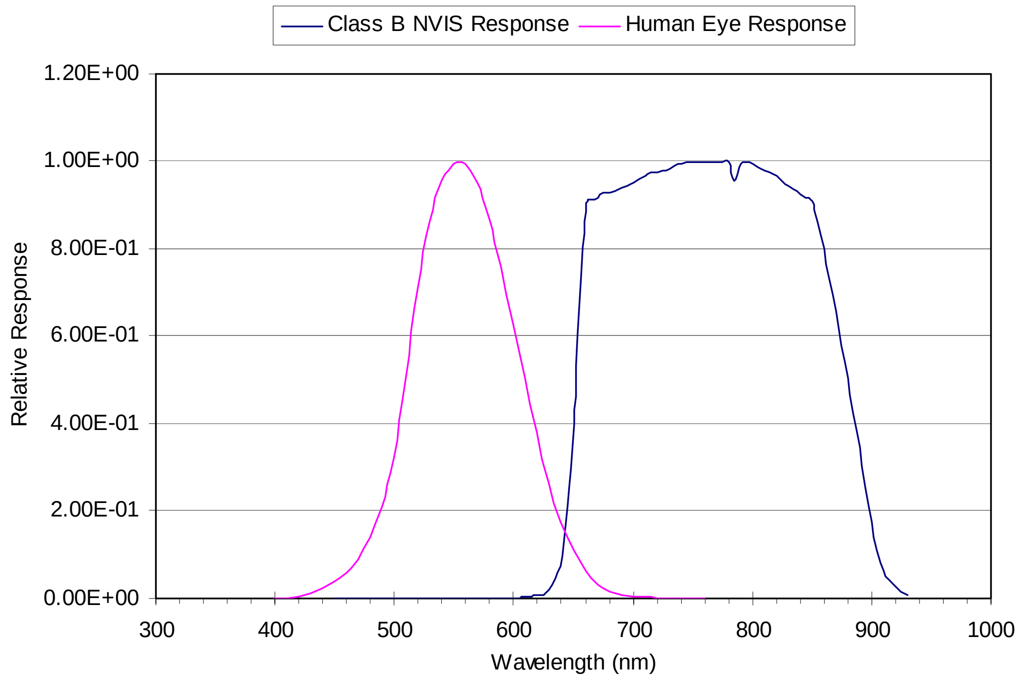

Figure 7. Releative Response of Human Eye and Class B NVIS

Firstly, restricting the wavelength of light in an aircraft cockpit to less than 675 nm (in the case of class C NVIS devices) restricts the designer on choice of lighting colors. Any light with wavelengths greater then 675 nm would not be available. Referring to Figure 5 we can see that this would eliminate red light and of course white light which includes shades of red. It is important to note that these colors must be pure with no contamination of white light. This has given rise to the development of many different colored plastic filters that create colors known as "NVIS yellow", "NVIS green", and "NVIS red" etc. Of course the lighting has to be usable when the cockpit is employed at night for unaided operations as well where certain colors have traditionally been used for various cockpit lights, i.e. red for fire lights. This creates problems for designers in that "NVIS red" is really more of a shade of orange.

Secondly, the lighting must still be usable, especially in the case of warning and caution lights, during day-time operations and during night unaided operations. This means that the lighting must have a minimum luminance at which it must maintain its NVIS compatibility. Given the requirement to be able to discern the status of red warning lights under the influence of direct sunlight, this can lead to conflicting design criteria.

Finally, not all NVIS devices are created equal. There is a certain amount of variance in each set of NVGs that will to some extent influence their individual performance. When setting light levels in an NVIS compatible cockpit, designers must keep this in mind.

Specification Governing NVIS Cockpit Design

General

Designing an NVIS compatible cockpit is a tradeoff between varying factors that all appear to be in competition with each other. The information laid out in MIL-STD-3009 attempts to set some guidelines by which cockpit lighting should be designed to ensure NVIS compatibility.

NVIS Radiance

The first item to discuss is the term of NVIS radiance that is used within MIL-STD-3009 to set the specifications for cockpit warning lights. NVIS radiance or NR_i, where i is the class of NVIS device, is a term that was created for the specification to measure the amount of energy being transmitted by an object that is visible to the NVIS device and is defined by the equation

$$\mathrm{NR}_i = G_{\max} \int_{450}^{930} G(\lambda)_i \, N(\lambda) \, d\lambda$$

where G_{max} is 1 mA/W and is a correction factor for units, $G(\lambda)_i$ is the relative spectral response of the NVIS device with *i* representing the class, and $N(\lambda)$ is the spectral radiance of the light source (U.S. DoD, 2001, 74). By multiplying $G(\lambda)_i$ and $N(\lambda)$ together, a plot is obtained detailing how much the two functions correlate. By integrating this plot with respect to wavelength over an interval of 450 nm to 930 nm[7], a measure can be obtained as to how much energy the light source is emitting that will trigger a response from the NVIS device. This is precisely the information that must be known to determine how much impact a particular light will have on the NVIS device. With this term defined, it can be used in the specification to set guidelines for the NVIS radiance of particular lighting components.

NVIS Radiance for Warning Lights

The specification for NVIS cockpit warning lights is laid out in Table III of MIL-STD-3009. An excerpt of the information contained therein is shown in Table 2. The selected excerpt contains data pertaining to warning and caution lights as well as generic primary lighting specifications for comparison purposes.

[7] This interval encompasses both spectral density functions and is thus the region where the product of the two functions would be expected to be greater than zero.

Table 2. Excerpt From MIL-STD-3009 NVIS Lighting Specification Table

Lighting Component	Type I Devices					
	Class A			Class B		
	Not Less Than: (nNR_A)	Not Greater Than: (nNR_A)	cd/m^2	Not Less Than: (nNR_B)	Not Greater Than: (nNR_B)	cd/m^2
Warning signal	50	150	51.5	47	140	51.5
Master Caution signal	50	150	51.5	47	140	51.5
Primary	---	0.17	0.343	Same as class A		

The value for the maximum nNR_B for primary lighting was determined by investigating the NVIS radiance for a defoliated tree. This was deemed to be the lowest contrast object an operator would need to be able to discern. A curve for the minimum spectral radiance was derived by multiplying the spectral radiance of starlight with the reflectivity of tree bark. Using this function in the equation for nNR_B (shown on page 26) yields a value of 0.17. Therefore, to be able to discern defoliated trees, the energy from any cockpit lighting source should not exceed that figure (U.S. DoD, 2001, 75).

However, exception is made for cockpit warning lights. The limitation for class A NVIS was selected for both class A and B since it is more stringent and commonality was desired. The relaxed value for warning lights was selected for three reasons. Firstly, the specification states that warning lights should be of a different color than primary lights. NVIS yellow is used for class A devices and will still cause some reaction from NVGs so it was argued that a relaxed specification should be applied. Secondly, the specification also states that warning lights should be illuminated to 51.5 cd/m^2 (to ensure adequate attensity[8]). The requirement for primary lights is only 0.343 cd/m^2 and therefore, to allow for the higher illumination requirement, the argument was made that nNR_B should be increased. Finally, for Type I NVIS devices, a warning light will usually be within the NVG FOV when it first activates. The specification argues that in that case, the radiance should be high enough to attract the operator's attention and therefore a minimum value for nNR_B was set as well.

MIL-STD-3009 also addresses specifications for operation of cockpit warning lights in a day-time environment. The requirement states that warning lights must be discernable in direct reflected specular sunlight. Additionally, in a diffuse environment, it must be possible to determine the status of the warning light under 10,000 fc of light. Obviously these demands are in direct competition with the requirements for an NVIS environment and the designer must strive to find an optimum balance for both situations.

It is these items of the specification that are being investigated in this paper. The decision was made at the inception of the project that complying with these requirements would ensure mission effectiveness and NVIS compliance. As shall be seen, supported by the data gathered during this evaluation, it is concluded that in this case it was required that the specification value be exceeded to satisfy all the demands of the cockpit design.

[8] Attensity is a term used to describe the effectiveness of the warning light for gaining the attention of the operator

CHAPTER III

METHODOLOGY

Objective

General

The evaluation conducted at AETE was executed over the course of two separate projects. The first project was a DT&E effort to evaluate candidate lighting configurations, provide data to the designers, and recommend potential design modifications. The second project was an evaluation of the final solution. Over the course of both projects, several different types of fire warning lights were evaluated.

This author was a member of the test team and the supervisor of the agency that conducted the evaluation. In this capacity, test missions were flown, post flight reports were written, and the final report was reviewed and approved.

Aim

The aim of this investigation was to correlate data gathered during the evaluation project conducted at AETE, reduce the data as applicable for validation of the thesis, conclude on any trends that became apparent in the reduced data, and make recommendations on the findings as they pertain to the utility of the fire warning lights in the NVIS environment.

Method

During the course of the two projects executed at AETE, five different fire warning light types were evaluated comprising four NVIS compatible designs, and the legacy lights used for comparison. Appendix C contains a description of these lights along with an image of each where available. Since the lighting data gathered in this thesis was collected solely for scholastic purposes, the manufacturer's names have been substituted with generic identifiers.

Data collection occurred in two different locations. Initial controlled data collection was conducted in the NVIS laboratory at AETE, Cold Lake, Canada. The NVIS laboratory is a multi-use flight test laboratory that can be sealed from all external light leaks and then illuminated to specific controlled conditions to recreate exact environmental lighting requirements. For instance, by setting the correct lighting levels, a clear, starlit night can be simulated to evaluate the system under investigation in those conditions. Further data were obtained in-flight employing the actual equipment being tested in real world conditions. Moon phase and illumination prediction software were used to ensure that, during the selected test times, the actual illumination amount was known.

The following sections describe the data that was required as well as the methods used to obtain it. Finally, the data reduction method is presented along with a rationale for the procedure. The procedure essentially involves the comparison of the five different fire warning light configurations over the course of equivalent evaluations. By comparing the results and knowing the specifications of each of the lights, conclusions may be drawn.

Required Data

To support the findings the following data were required. These data requirements were selected by virtue of the fact that they could provide evidence that would help determine the suitability of each lighting solution with regard to the competing requirements of NVIS compatible cockpit design, namely, day-time effectiveness, unaided night-time effectiveness, and NVIS aided night-time effectiveness.

Manufacturer's Warning Light Specifications

For all the lights involved in the comparison, it was necessary to know the manufacturer's specifications for the lighting devices. The required specification value was NR_B if it was available.

Daylight Effectiveness Data

Daylight effectiveness data was obtained to evaluate each particular solution for its compatibility with day-time operations. The data that was required is shown in Table 3.

This data was required to determine the effectiveness of the particular light in direct sunlight conditions as required by MIL-STD-3009. This requirement addressed the need to evaluate the conflicting design requirement for effectiveness during day-time operations as well as aided NVIS night-time operations. The data was to consist of quantitative measurements taken on the ground as well as mission representative qualitative data taken during airborne flight test.

Table 3. Daylight Data Requirements

Data Requirement	Description
Attensity	A term used to define the effectiveness of the light at attracting the attention of the operator.
Readability	A term used to define how easily the information on the light (i.e. labeling etc.) could be determined.
Discernability	A term used to define the ease with which the status of the light (illuminated or not) could be determined.

NVIS Laboratory Ground Test Data

NVIS laboratory ground test data was obtained to evaluate each particular lighting solution for its compatibility with night-time operations. The laboratory provided the opportunity to take measurements in a controlled environment. The same data detailed in Table 3 was required during this test for unaided night-time operations. In other words, investigation of the effectiveness of the fire warning lights during night-time operations where NVGs are not employed.

In addition to the data already described, visual acuity data using the NVGs was also required with the fire warning lights both extinguished and illuminated. By comparing extinguished and illuminated data points for each light in question a measure could be obtained that would give an indication of how much impact the illuminated light was having on the NVG effectiveness through activation of the AGC. This data was to consist of both quantitative data (using the U.S.A.F. tri bar system as detailed in the next section) as well as qualitative evaluator comments.

Night-time Effectiveness Data

Night-time effectiveness data was obtained to evaluate each particular solution for its compatibility with night-time operations. The data that was required is shown in Table 3.

This data was required to determine the effectiveness of the particular light during aided and unaided night-time operations. This requirement addressed the need to evaluate the conflicting design requirement for effectiveness during night-time operations as well as day-time operations. The data was to consist of qualitative data taken during airborne flight test.

Data Collection Method

The following data collection methods are in accordance with MIL-STD-3009. The information in this section will explain the procedures and highlight the specifics that were peculiar to the project carried out at AETE.

General

Much of the data gathered in this evaluation was qualitative in nature. Even the data that was considered quantitative still relied to certain extent on the opinion and interpretation of the evaluator conducting the measurements. As such, the more evaluators that could complete the measurements the less chance there would be that the data would get skewed by a single individual's opinion. As such, all the evaluations were, to the greatest extent possible, conducted by a team of four qualified test pilots (of which the author was one) and two qualified flight test engineers.

As was mentioned in the last section, day and night effectiveness of the individual lighting solutions was evaluated against the three criteria listed in Table 3. To ensure continuity of interpretation of the effectiveness of each of the criterion by each evaluator, a compensation scale was developed by the test team. This scale is shown in Table 4. The numerical assignment made to each category allowed the results to be presented graphically to portray the relative effectiveness of each lighting solution. The scale involved the evaluator determining firstly, whether each criterion was even possible to rate and secondly, if it was possible to rate, how much compensation was required as a measure to how effective the light was for each of the criterion. Compensation could involve such things as moving head position, squinting, or shading the light with a hand etc. Night evaluations were conducted in the configurations detailed in Table 5.

Prior to commencing any evaluation in the aided configuration evaluators were asked to initialize and adjust their NVGs to a standard configuration. This involved adjusting the device so that the diopters (see Appendix A) were adjusted for the

Table 4. Evaluation of the Lighting Rating Criteria

Criteria	**Rating**			
	1.00	**0.67**	**0.33**	**0.00**
Attensity	Good	Moderate	Poor	Nil
Readability	Readable	Difficult – Minor compensation required	Almost Unreadable – Major compensation required	Unreadable
Discernability	Discernable	Difficult – Minor compensation required	Almost Indiscernable – Major compensation required	Indiscernable

Table 5. Aircrew Test Configurations

Configuration	Description
Aided	• Cockpit lighting set to an operationally representative level. This was specified and remained the same for all evaluators. • NVGs donned and placed in the lowered position.
Unaided	• Cockpit lighting set to an operationally representative level. This was specified and remained the same for all evaluators. • NVGs doffed and stowed.

individual user and the objective lens was focused at infinity to ensure an initial visual acuity (VA) at a Snellen fraction[9] of at least $\frac{20}{25}$. This adjustment is standard procedure for operational use of the NVGs and ensured that each evaluator was conducting tests from a standard baseline configuration.

Daylight Effectiveness Data

Daylight effectiveness data was collected qualitatively both on the ground and in the air. This section will outline the techniques employed in both cases.

For ground measurements, the aircraft was placed in the following conditions;

1. Inside an aircraft hangar with the lights on and the hangar doors closed.
2. Ground power applied to the aircraft.
3. Evaluator exposed to daylight conditions for 5 minutes prior to the test.
4. Aircraft lighting set to off.

[9] See the section entitled "VA Data Reduction" in this chapter for a full discussion on VA and Snellen fractions.

5. Seat height adjusted to design eye level for each individual evaluator to place eye level at 109 cm above the cockpit floor.

Measurements were made to verify that the illumination of the fire warning light was discernable in 10,000 fc[10] of light which is equivalent to that of direct sunlight (U.S. DoD, 2001, 65). The measurements were made by holding a 600 watt (W) Lowel Omni-Light to cast 10,000 fc of light on the illuminated fire warning display as shown in Figure 8. An illumination meter was used to ensure that exactly 10,000 fc of illumination was used. The evaluator was asked to indicate an assessment for attensity and discernability in these conditions. All measurements were made using a darkened helmet visor as would be the case during representative operations. This would be the worst case in terms of daylight discernability.

Figure 8. Daylight Effectiveness Testing

[10] The symbol fc represents the unit foot-candle and is a measure of the intensity of a light source.

Airborne evaluations were carried out by placing the aircraft at such an attitude that direct sunlight would shine on the illuminated fire warning lights. By using the light test switch the fire lights could be illuminated. Evaluators were asked to make the same assessments that had been made on the ground under controlled conditions in order to confirm the results as assessed in real sunlight.

<u>NVIS Laboratory Data</u>

NVIS laboratory data was collected quantitatively and qualitatively in both aided and unaided configurations. For both configurations the aircraft was established in the following conditions;

1. Darkened hangar conditions of 0.002 ± 0.001 mLux[11]. A Night Sky Simulation System was used to maintain between 0.16 and 0.17 nNR which was the equivalent of a starlit night.

2. The aircraft was attached to ground power.

3. The evaluator was adapted to night conditions for 20 minutes prior to conducting the test.

4. The evaluator adjusted the cockpit lighting to an "operationally suitable" level. Without detailing the intricacies of the CF-188 cockpit, this was the same settings for all evaluators.

5. The seat height was adjusted to a design eye level setting the evaluators eyes at 109 cm above the cockpit floor.

For the unaided evaluation, each evaluator was asked to make assessments for attensity, readability, and discernability as previously detailed. For the aided evaluation, evaluators were asked to make assessments for attensity and discernability only. In addition they were also asked to assess VA with and without the fire warning lights illuminated. The VA test was conducted using the USAF tri-bar board. This board is shown in Figure 9.

[11] The symbol mLux represents mili-lux and is a measure of the intensity of a light source.

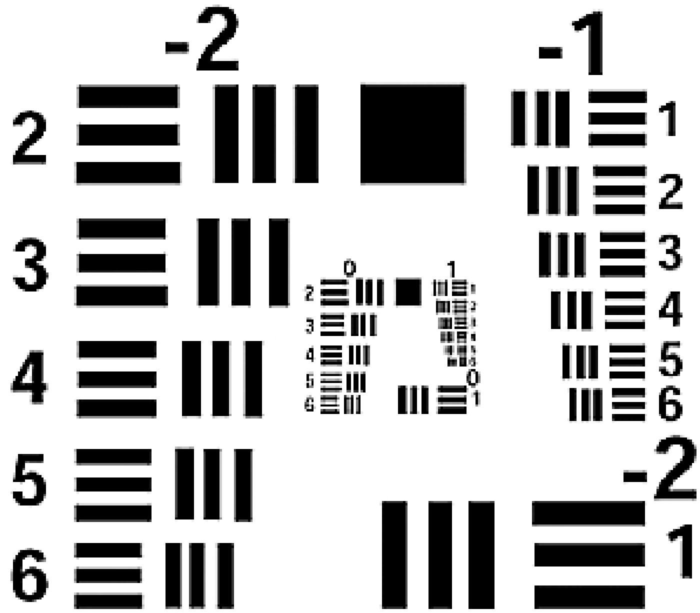

Figure 9. U.S.A.F. 1951 Tri-Bar VA Evaluation Board

The board was placed at positions 1, 2, and 3 as shown in Figure 10. Evaluators were asked to firstly note the smallest vertical and horizontal pair that they could discern (i.e. -1, 6) with the fire warning light extinguished. They were then asked to illuminate the light and determine whether there had been any degrade in VA by again noting the smallest set of bars that could be discerned[12].

Night-time Effectiveness Data

Night-time effectiveness data was collected during airborne operations to determine the impact of the fire warning lights on representative operational maneuvers. The evaluations were made in both the aided and unaided configurations. The following maneuvers were conducted;

[12] The actual meaning of each pair of lines is discussed in the sections "VA Data Reduction" in this chapter.

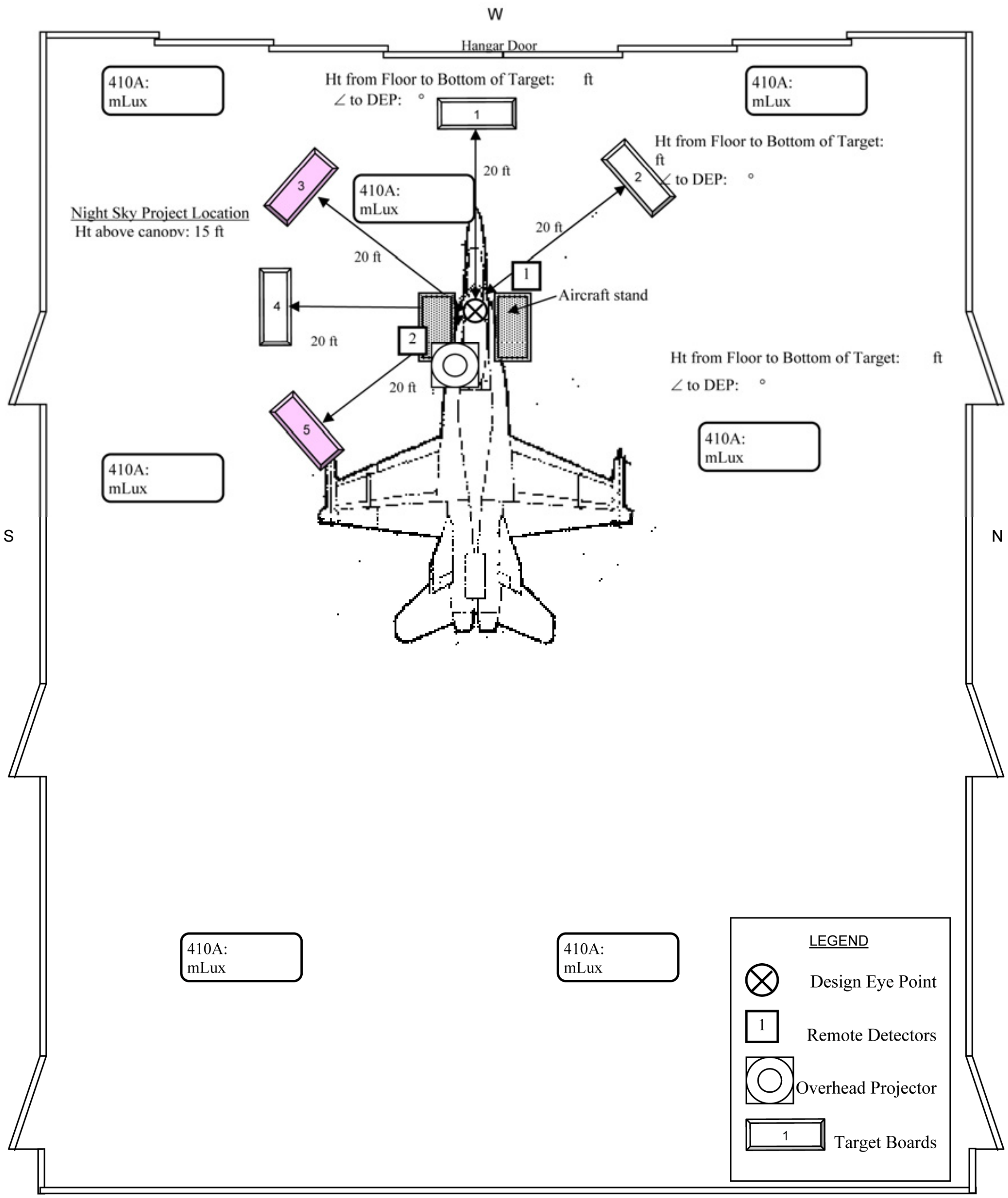

Figure 10. NVIS Laboratory Setup

1. Night airborne intercepts of a simulated enemy aircraft.
2. Night formation flight at a distance ranging from approximately 7 ft to 1 ½ NM.
3. Low altitude flight at 1,000 ft AGL.
4. Simulated night ground attacks using dive angles of up to 30° remaining above 5,000 ft AGL.

During these maneuvers, the fire warning lights would be activated to determine what effect this would have on satisfactory completion of the task. Additionally, crews were asked to make evaluations on attensity, readability, and discernability. The evaluations for attensity and discernability were to be made during the maneuvers described above in both the aided and unaided configurations. The evaluation for readability was made in the unaided configuration only and completed during straight and level flight.

Data Analysis and Reduction

Much of the data collected during this evaluation was qualitative in nature. As was detailed above, every attempt was made to try and standardize the responses given by each evaluator and to set a baseline lighting configuration under which all of the evaluations were to take place. Additionally, all but one member of the team had little or no experience flying with NVIS devices and so the entire evaluation team was essentially starting from the same point-of-view when it came to rendering an assessment. Finally, training was conducted prior to the evaluation to ensure that all members of the team understood the definitions detailed in Table 4 and, as much as possible, understood the definition of minor and major compensation.

Attensity, Readability, and Discernability Data Reduction

This data comprised of two types: the quantitative value assigned to the criterion and the evaluator comments. The quantitative data was presented in a graphical format as shown in Figure 11. The data represents the average score of all evaluators for each of the criterion, evaluated against each of the lighting options that were investigated. The shaded gradient in the background of the graph is an approximation of how acceptable the rating was with respect to mission effectiveness with green being acceptable and red being unacceptable. A plot was made as required for both evaluator configurations (as described in Table 5) and for all types of test that were conducted. In this manner, a comparison could be made of how each lighting solution would score as on overall compromise to the competing demands placed on the system as a solution for an NVIS

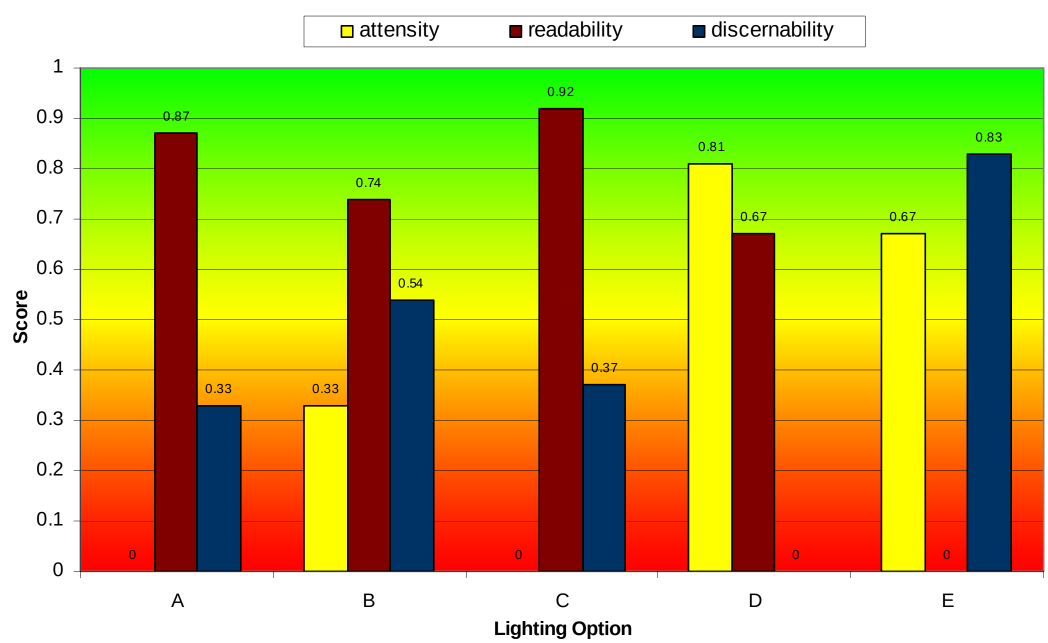

Figure 11. Sample Attensity, Readability, and Discernability Data

compatible cockpit. Only comments that appeared to be a common theme to all evaluators were included in order to try and filter out any outlier data points; however all comments were analyzed to ascertain their validity even if they appeared to be a sole observation by only one evaluator. Evaluator comments were also tabulated with trends noted in narrative format.

VA Data Reduction

This data was collected as a "before and after" record of the VA data as rated against the U.S.A.F. tri-bar VA board shown in Figure 9. By recording how many levels of VA, if any, were lost when the fire lights were illuminated, it was possible to get a quantitative measure of the impact the lighting solution was having on the performance and effectiveness of the NVGs.

Standard Snellen VA data is expressed as a fraction. For instance, a Snellen VA measurement of $\frac{20}{40}$ means that the observer can discern at a distance of 20 ft only that level of detail that an observer with normal sight will see at a distance of 40 ft, in other words $\frac{20}{40}$ represents a VA of below normal human ability. The U.S.A.F. tri-bar data was converted to standard Snellen VA figures since this is a more generally accepted means by which to record such data and is commonly used by ophthalmologists to characterize the VA of a human subject. Pinkus and Task of the Air Force Research Laboratory at Wright-Patterson AFB, OH detail the following method for making the conversion. In physical terms, normal human VA has been defined as the ability of the eye to resolve detail that corresponds to a separation between two lines equivalent to the distance subtended by an arc of 1 arcmin. On the U.S.A.F. tri-bar chart used for this evaluation, the horizontal and vertical line pair that corresponded to this value was pair 1 in set 0 (i.e. 0,1). The tri-bar chart is constructed such that each pattern above or below 0,1 is larger or smaller by a factor of $\sqrt[6]{2}$. Since there are 6 line pairs in each set this means that the first pair in a set is half the size of the first pair in the previous set (i.e. pair -1,1 is half the size of pair -2,1). Therefore, since pair 0,1 corresponds to a Snellen value of $\frac{20}{20}$, it follows that pair -1,1 corresponds to a Snellen VA of $\frac{20}{40}$. In other words, the line spacing is twice as wide corresponding to an arc of 2 arcmin (Pinkus and Task, 1998, 2). From this it can be derived that the formula for converting a particular pair of line patterns in the U.S.A.F. tri-bar chart to a Snellen VA fraction is

$$\frac{20}{10 \times 2^{\left(\frac{7-k}{6}\right)} \times 2^{-j}}$$

where j is the set number (a possible integer value of -2 through 1) and k is the number of the pattern within a set (a possible integer value of 1 through 6). Thus, the standard Snellen fraction can be derived for all of the observed measurements made during this evaluation and relevant conclusions drawn expressed in the commonly accepted Snellen VA form. Table 9. in Appendix D shows the converted values for the U.S.A.F. tri-bar chart.

A plot was also made for the VA data to show the relative degradation (if any) for all of the lighting solutions. Since the legacy lighting system was not NVIS compatible and since it was to be the benchmark for which the NVIS compatible lighting could be measured against, the VA degrade that would be experienced with the legacy fire lights illuminated was considered to be the maximum relative degrade and was scored with a normalized value of 0. By comparing the degrade in VA experienced with all of the other lights, a relative degradation could be scored with respect to that experienced with the legacy lights. In that way, a normalized score of 1 would represent no VA degrade and a value of between 0 and 1 would represent a relative degrade in proportion to the loss experienced with the legacy lights. In this manner a graph could be displayed that would portray a relative, normalized comparison of all of the lighting options.

Evaluator Comments

Evaluator comments during all phases of the evaluation were collated and trends were examined. As with the comments solicited for attensity, readability, and discernability, any outlier data points were examined and researched to ascertain their validity. The comments were then assessed and presented with respect to the impact the observation would have on the type of mission representative maneuvers that were conducted during airborne testing.

CHAPTER IV

RESULTS AND DISCUSSION

Testing occurred between September 2004 and November 2005 and was conducted at cold Lake, AB, Mirabel, QU, and Comox, BC. The results detailed in this section provide the data that were obtained for each of the required categories as listed in Chapter III.

Manufacturer's Specifications

Results

For the five lighting options that were evaluated the manufacturer's specification for nNR_B is detailed in Table 6. Since there was no means available for the test team to gather nNR_B data, all the information was furnished by the contractor.

Discussion

This data clearly shows that a complete cross section of lighting variants was evaluated. The legacy fire lights, although clearly not NVIS compatible, were evaluated

Table 6. Manufacturer nNR_B Data for Tested Lighting Solutions

Lighting Solution	**nNR_B**	**Remarks**
Legacy Fire Lights	Not Applicable	Not NVIS compatible and therefore no measurements were ever taken.
Feasibility Study Lights	$47 \leq nNR_B \leq 140$	
Rev-1	116.4	
Rev-2	125.9	
Rev-3	10,100	

as a baseline for daylight data. These were the fire lights that had been in the aircraft since its inception and were designed for operation in daylight conditions. They would provide the standard for which the other lighting solutions could be compared against for effectiveness in direct sunlight.

The feasibility study lights were stated as being within the specification limits. From this it follows that the value for nNR_B must have been between 47 and 140 as stated in MIL-STD-3009. The nNR_B for the Rev-1 lights was stated as being a value of 116.4. This provided two evaluation options that fell within the stated specification. The nNR_B for the Rev-2 lights was stated as being a value of 125.9 which was close to the maximum nNR_B of 140 permitted by MIL-STD-3009. This provided an evaluation option that fell at the maximum value of the specification. Finally, the Rev-3 lights had a value for nNR_B of 10,100 which was approximately seventy times greater than that of the Rev-2 lights. This provided an evaluation option well above the specification value.

Daylight Effectiveness

<u>Results</u>

For daylight effectiveness testing, readability data was not recorded. It was considered that in full daylight this would not be of concern since it would be easy to read the characters on any of the lighting options at 10,000 fc which in fact turned out to be true. Evaluations for attensity and discernability are presented in Figure 12 with results also included for the legacy fire lights to provide a baseline for comparison.

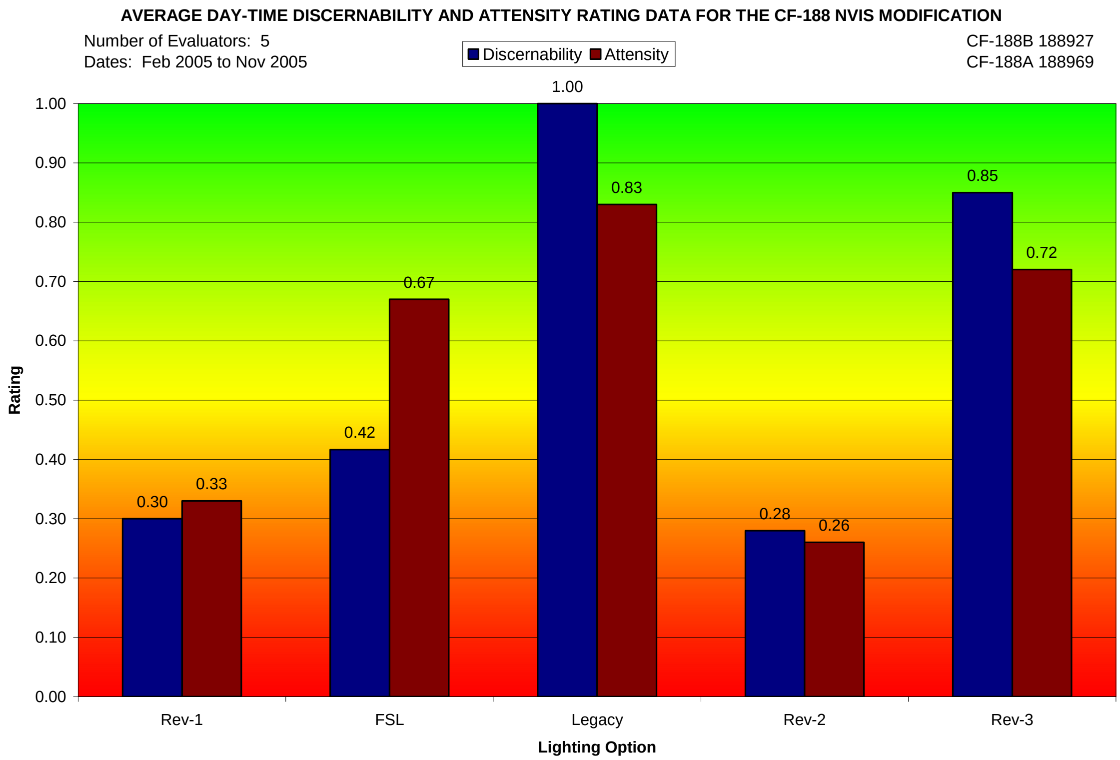

Figure 12. Daylight Discernability and Attensity Data

For the Rev-1 and Rev-2 lighting options, the average evaluator rating placed them at a rating of almost indiscernible (≤ 0.33). With the light being almost indiscernible there was a correspondingly low attensity rating to match since without being able to see the light the evaluator stood no chance of being attracted by it. Evaluator compensation ranged from significant head movements of up to 5 or 6 inches to dedicating one hand to shield the sun light in order to be able to discern the warning light status. This would severely hamper a combat pilot during the conduct of a mission task since he would only have one available hand with which to conduct mission related functions.

The feasibility study lights faired slightly better in their ratings for daylight effectiveness although they still only achieved an average discernability rating just above almost indiscernable. Similar compensatory measures were required by most evaluators with the incumbent impact on mission effectiveness. The feasibility study lights appeared to fair slightly better by virtue of their backlit design as described in Appendix C. This design provided a greater area of the light that was illuminated which helped provide better attensity ratings. However, the backlit design of the light also had a significant detracting behaviour. The light appeared to collect the incident sunlight and re-reflect the energy giving the appearance that the fire light was illuminated whereas it in fact was not. This characteristic was deemed unsatisfactory since it would provide confusing input to the operator by providing a false fire indication which could prompt an incorrect response from aircrews. Responding to a false fire light could result in shutting down a normally functioning engine and needlessly aborting a mission.

The Rev-3 fire lights performed quite well during daylight effectiveness testing posting average scores that were between difficult and discernable for the discernability criterion, and better than moderate for attensity. Only very minor compensation for discernability was reported consisting of small head movements with no requirement to shield the lights thus allowing the operator uninterrupted use of both hands for mission tasks.

The Rev-2 and 3 fire lights also incorporated a prismatic faceplate angled such that it would deflect specular reflections away from the pilot’s eyes. Although this feature certainly helped with day-time readability it was not sufficient in the case of the

Rev-2 lights to render the design satisfactory for day-time operations. It appeared that the increase in nNR_B furnished in the Rev-3 lights was also required to make this option acceptable.

Discussion

The Rev-1, Rev-2, and feasibility study fire lights were clearly not acceptable for day-time use. The lights were extremely susceptible to washout under direct sunlight conditions which would prevent an operator being able to consistently discern the status of the light. Even if accompanied by a cockpit generated voice caution (as is the case in the CF-188) there would still be a delay in the pilot reacting to the appropriate lighted fire switch which could prove catastrophic in a fire situation since activating the fire extinguishing system relied on pressing the correct fire switch. Additionally, the back lit design of the feasibility study lights proved susceptible to reflections caused by direct sunlight giving the impression that the light was illuminated when it in fact was not. This false lighting condition was also considered unsatisfactory.

The Rev-3 fire warning lights proved to be the only NVIS lighting solution that was compatible for day-time use. Although the lights were not considered to be as discernable in daylight conditions as were the legacy lights, they were still easier to discern on average than a rating of difficult and certainly provided a satisfactory solution. This is understandable since the legacy light design was not made with NVIS compatibility in mind and the luminance of the lights could be made such that 10,000 fc of direct light would not affect them. That luxury did not exist for the designers of the Rev-3 lights and they were deemed acceptable for day-time operations. With evaluator compensation techniques being limited to small head movements and perhaps ½ sec of extra dwell time on the light to discern its status there was negligible impact on mission effectiveness.

NVIS Laboratory Ground Test

Results

All of the lighting options were evaluated for attensity, readability, and discernability in both the aided and unaided configurations. The average rating for all lighting configurations for the readability criterion was 1.0. None of the evaluators reported difficulty being able to read any of the lights. The results for discernability and attensity are presented in Figure 13.

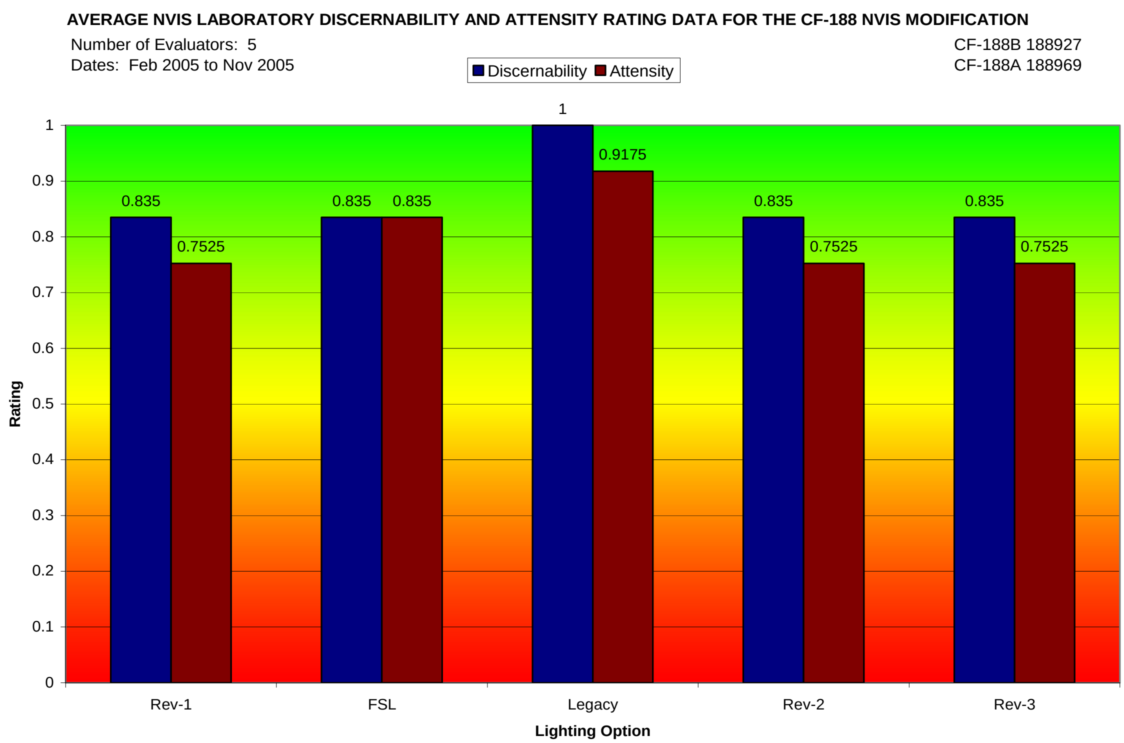

Figure 13. NVIS Laboratory Aided & Unaided Discernability & Attensity Data

There were only one to three evaluators for each criterion that rated less than 1.0 with attensity being the most criticized criterion; however, even for this criterion the worst rating assigned was that of moderate attensity which was still deemed satisfactory for the mission. Compensation techniques cited focused on extra dwell time when viewing the light to determine its status. Additional dwell times were cited as being an absolute maximum of ½ sec which was not deemed to be of impact to mission effectiveness.

The data for average evaluated normalized VA are presented in Figure 14. As can be seen, when compared to the loss in VA experienced when the legacy fire lights were

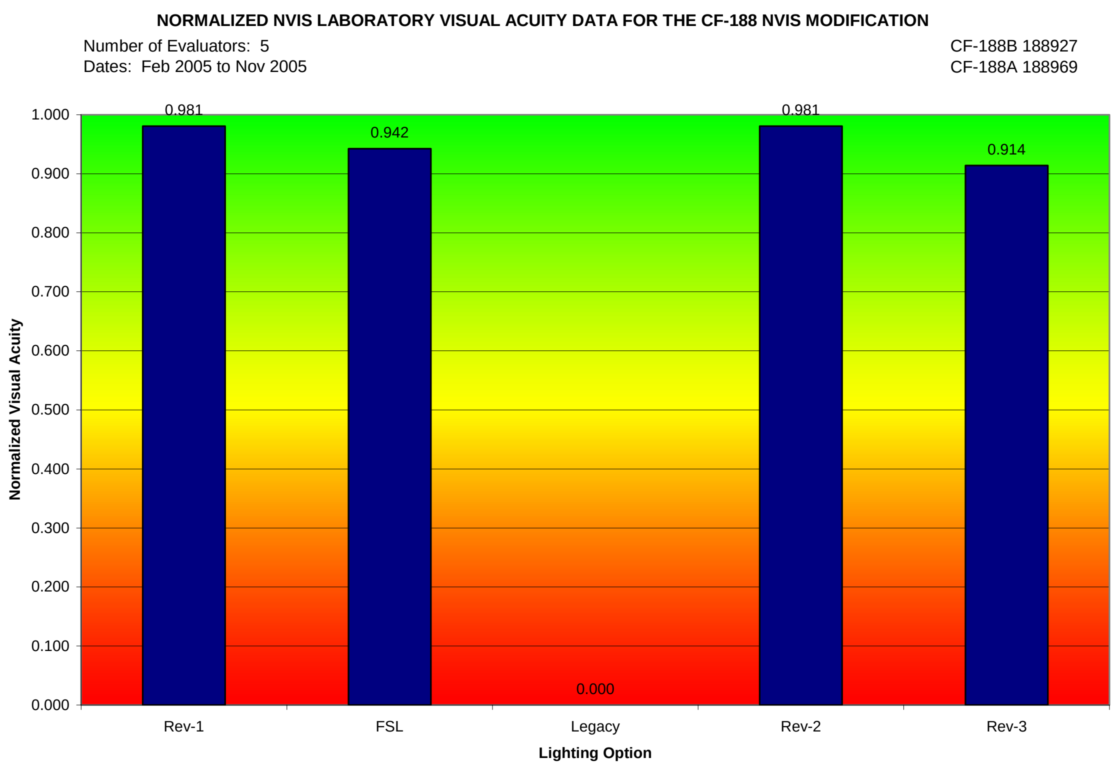

Figure 14. NVIS Laboratory Aided VA Data

illuminated, all the other lighting options were satisfactory. For the Rev-1, Rev-2, and feasibility study lighting options only one evaluator reported any loss of VA and in all cases except for one this was only a drop of one line pair on the U.S.A.F. tri-bar board.

The lowest VA rating of all the lighting options was for the Rev-3 lights. These lights were at a higher nNR_B than all the other lighting options. The average drop in VA was reported to be from line set 0,0 to -1,6. This corresponded to a Snellen equivalent drop of $\frac{20}{20}$ to $\frac{20}{22}$. The worst decrease in VA occurred when viewing the U.S.A.F. tri-bar board when placed directly in front of the aircraft. In this case a degrade from 0,1 to -1,4 was reported. This corresponded to Snellen equivalent drop of $\frac{20}{20}$ to $\frac{20}{28}$.

The only evaluator comments that were noted were with the Rev-3 lights. Evaluators reported that with the Rev-3 lights illuminated a slight haze was observed in the NVGs that caused a barely noticeable activation of the AGC. It was reported that this was not considered to detract from mission effectiveness since it was only barely noticeable and did not cause an objectionable decrease in VA.

Discussion

All of the lighting options evaluated were considered to be acceptable in terms of readability, discernability, and attensity. With reference to the data and evaluator comments there was no clear preference toward any individual solution. Required compensation, if any, was negligible and considered a minor annoyance at worst.

In terms of VA all of the lighting options were again considered acceptable and in no way detracted from mission effectiveness. The data for the Rev-3 option warrants further discussion since it did appear to be noticeably lower than the other options. Firstly, the average drop in VA was only equivalent to a drop in Snellen fractions from $\frac{20}{20}$ to $\frac{20}{22}$. Although this did represent degraded performance, and although consistent degradation was not experienced with any of the other options, the degradation was extremely small and was not considered to detract from mission effectiveness. Considering that this lighting option was the only satisfactory solution in terms of daylight effectiveness, the very slight degrade in VA as a result of the increased nNR_B was certainly acceptable. Additionally, considering that a fire light will only illuminate very occasionally, the degraded VA was really insignificant for overall mission effectiveness.

The greater degrade experienced through the front of the cockpit was likely due to the fact that there was almost no canopy shroud available at that point in the cockpit to shield the light. Again however, the degradation was very small and caused a decrease to $\frac{20}{28}$ on only one occasion. This was still quite acceptable considering that a VA of only $\frac{20}{25}$ is expected when calibrating the AN/AVS-9 NVGs prior to an operational mission. As well, since this assessment occurred only once and with only one evaluator, there is a chance that the particular pair of NVGs employed may have been older and not performing as well as some of the other pairs used. In short, although not perfect and although very slightly worse performing in terms of NVIS compatibility than the other options considered, the Rev-3 option was entirely satisfactory and was not considered to be a hindrance to mission effectiveness.

Night-time Effectiveness

General

This was the last phase of the evaluation to be completed and took place at deployed locations on the West coast of Canada. This was required in order to find a geographic location that would have the required lighting environment for the test to take place in as discussed in Chapter III. CF-188 flight time is very expensive and as well, there was only limited time available to conduct all flight testing. It was explained earlier in this paper that the data used to support this thesis was only one small part of very much larger program; the entire exterior lighting system was modified and required extensive testing as well.

Consequently, the decision was made only to test the Rev-2 and Rev-3 lights during aided and unaided night-time operations. Two aircraft were employed in the testing, one with the Rev-2 fire lights and one with the Rev-3 fire lights.

Results

Night-time readability, attensity, and discernability testing was conducted in the unaided configuration. No differences were noted from the testing that took place in the NVIS laboratory and thus the measurements that had been made there were confirmed.

As a result, both lights were considered to be acceptable for use in the cockpit during unaided night-time operations.

During aided operations however, the Rev-2 fire lights were unsatisfactory for attensity. Due to schedule delays in testing there was never an opportunity to take quantitative measurements for attensity and discernability and so the only data available are evaluator comments. When viewing the Rev-2 fire lights through the NVGs (as would be the case when the light first illuminates), there did not appear to be any difference between it and any other NVIS compatible light in the cockpit. Since the NVG image is monochrome, and since all images very close to the objective lens are blurry (a result of the fact that the NVGs are focussed at infinity), there was no way to identify the light within the myriad other lights on the instrument panel. Even though they were at the MIL-STD-3009 NVIS radiance value they did not appear qualitatively brighter than any of the other lights. All evaluators felt that if the light illuminated whilst within the NVG FOV it would not attract their attention.

There was no observed negative impact of the Rev-2 fire lights when illuminated whilst the observer was attempting to view objects external to the aircraft. All tasks detailed in chapter III were completed without hindrance.

The Rev-3 fire lights were also only able to be evaluated qualitatively. When viewed through the NVGs the illuminated Rev-3 fire light was noticeably brighter than any other light in the cockpit. As soon as the light would illuminate evaluators reported that it was immediately noticeable and certainly attracted their attention. In this respect the light served its purpose. When the Rev-3 light was illuminated whilst viewing objects external to the aircraft evaluators reported that there was a slight misting effect noticed in the NVG image. This was consistent with observations in the NVIS laboratory; however while the misting effect was not desirable it did not detract from mission effectiveness. When performing the mission representative tasks detailed in chapter III with the lights extinguished and then again with the lights illuminated there was no impact on mission effectiveness. Moreover, evaluators reported that the increased intensity of the light actually drew their attention to a fault in the aircraft, without detracting from the task at hand, thus proving to be more effective at warning of a fault.

Discussion

The Rev-2 fire lights evaluated in this phase of testing clearly demonstrated that they were NVIS compatible. During all mission representative tasks they did not at all degrade the evaluator's effectiveness at accomplishing the assigned task. There was one major failing of these lights however, and that was their poor attensity characteristics. When the Rev-2 fire lights were within the NVG FOV they did not attract the evaluator's attention. The specification value that has been set for warning lights is such that the light should appear brighter than other cockpit lights in order to provide an alerting mechanism to aircrews. The results of this evaluation however, showed that the maximum specification value for nNR_B that the Rev-2 lights were manufactured at was not sufficient to distinguish them from other lights in the cockpit. In the case of the Rev-2 fire lights, this situation could lead to a significantly delayed or incorrect response to an engine fire situation resulting in disastrous consequences.

The Rev-3 fire lights evaluated in this phase of testing demonstrated that they were certainly satisfactory for a single cockpit fighter aircraft at night in a combat mission environment. Whilst there did appear to be some contaminating light emitted from these lights, it was not of a sufficient quantity to degrade the mission effectiveness. The lights were entirely satisfactory for attracting the attention of aircrew in a fire situation. The higher nNR_B value was not detrimental to other mission tasks. This observation is further supported by the fact that fire lights should only illuminate in an emergency situation which should be a very rare event. The fact that the Rev-3 light could provide the warning it was designed to with only negligible impact on the performance of the AN/AVS-9 NVGs made it a suitable choice for this type of NVIS compatible cockpit.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Discussion

Daylight Effectiveness

The Rev-3 lights were clearly the best performing lights for daylight effectiveness whilst still maintaining satisfactory NVIS compatibility. Although the prismatic face plate certainly helped their effectiveness in daylight operation, it was not the main contributing feature for their effectiveness. This was evidenced by the poor performance of the Rev-2 lights that employed the same prismatic face plate but yet did not achieve satisfactory day-time effectiveness ratings. The main difference in the Rev-3 lighting option was the higher value of nNR_B and thus it must be concluded that this played a major part in the satisfactory day-time performance of these lights. As has been mentioned, the design of an NVIS cockpit is a compromise between competing demands. The evidence presented shows that to achieve day-time effectiveness of fire warning lights, using a higher value for nNR_B than that suggested by MIL-STD-3009 can help attain a satisfactory rating.

NVIS Laboratory Results

All of the NVIS lighting options investigated exhibited satisfactory characteristics in the NVIS laboratory. All provided adequate readability, attensity, and discernability characteristics in the unaided configuration. There was very little loss in VA between the extinguished and illuminated condition of the fire warning lights. For all of the lights except Rev-3, only one evaluator reported any loss and even that was considered negligible. The illuminated Rev-3 lights did produce slightly more VA loss. Since the only major difference between the Rev-3 lights and the others was the higher value for nNR_B it is likely that this is what caused the greater loss. However, although the loss was slightly greater than for other lights it was still considered negligible. The worst VA that was achieved was $\frac{20}{28}$ and this was only for one evaluator on one occasion. When considering mission effectiveness none of the evaluators considered the slight degradation to be of consequence.

Again, NVIS cockpit design comes down to a compromise; the higher value for nNR_B that appeared to provide the illumination required for satisfactory day-time effectiveness caused a slight, but inconsequential degrade to night-time aided VA. Given the conflicting design requirements, it was considered that this compromise was more than acceptable.

Night-time Effectiveness

The results achieved during night-time effectiveness testing confirmed what had been observed in the NVIS laboratory. The higher value for nNR_B of the Rev-3 lights, although noticeable, did not detract from mission effectiveness. Evaluators did notice slight effects of light contamination in the NVGs but this did not interfere with the maneuver being carried out. This was especially true when considering that the fire lights would only illuminate in an emergency and would not be a constant source of lighting in the cockpit.

Additionally, the higher value of nNR_B produced an average rating of better than moderate for attensity. This was welcomed since it permitted the fire light to perform its function and attract the pilot's attention when it was illuminated. None of the other lights evaluated were able to accomplish this. This is yet one more example where the higher value for nNR_B was successful in meeting the conflicting demands of NVIS cockpit design.

Conclusion

The thesis of this paper dealt with the conflicting design requirements faced by NVIS compatible cockpit designers. Cockpit warning lights, whilst meeting the requirements for compatibility with NVIS devices at night, must also maintain their ability to provide aircrew with adequate warning of emergency situations and still be capable of adequately furnishing all of these functions during the day as well.

The specification guidelines in MIL-STD-3009 have placed limitations on the NVIS radiance for warning lights to try and meet those demands. Even still, the challenge remains for designers to meet the needs of conflicting requirements for day and night operations in one complete solution. The evidence provided in this paper has shown that it is possible to exceed the specification requirements of MIL-STD-3009 in order to satisfy those conflicting demands. It has been shown that exceeding this specification for the case of a single seat fighter sized cockpit did not degrade the effectiveness of the conduct of combat missions for those types of aircraft. Moreover, it was demonstrated that in this case exceeding the specification for nNR_B was actually required in order to ensure adequate performance of the warning lights in attracting the pilot's attention.

At this stage it should be acknowledged that another potential solution to the compromise that must be created by the designer is to use a variable intensity lighting system that responds to detected ambient light levels and adjusts the warning light radiance accordingly. Indeed it has been acknowledged that there is certainly more than one method by which to tackle the compatibility difficulties that have been described. However, it must be remembered that the attraction of using NVGs in a modern combat aircraft is the low cost compared to the significant benefit that can be realized. Additionally, the modifications that have been described occur to an existing aircraft and are not incorporated at the aircraft design prototype stage. As such, an ideal solution is simple and elegant requiring minimal and low cost modifications. A variable intensity lighting system, whilst potentially effective, is significantly more complex and costly than the solution that has been proposed.

It should also be noted that it is not the intent of this paper to the question the validity of MIL-STD-3009. Indeed MIL-STD-3009 is an authoritative guideline that serves as excellent reference for any NVIS compatible design. However, MIL-STD-3009 does suggest in several cases that there is leeway for the acquiring agency to make decisions based on it's specific requirements especially concerning the inclusion of red warning lights (U.S. Dod, 2001, 78). It has therefore been the intent of this work to provide the experience that was gained as part of the CF-188 NVIS modernization to suggest specific details of where excursions can be made from the specification to satisfy the many conflicting demands that are placed on NVIS cockpit designers.

Recommendations

Specification Value

Based on the evidence presented it is recommended that exploring values for the NVIS radiance of cockpit warning lights outside the limits suggested by MIL-STD-3009 may be of benefit for the designers of future NVIS cockpit modifications. It appears that there is room to move on the value for NVIS radiance and that perhaps this might alleviate potential problems at an earlier stage in the design process preventing costly reworks and schedule delays.

Further Investigation

The value of nNR_B at a point seventy times greater than that of the specification appeared to be a good balance for all the conflicting demands of the NVIS design. Certainly in the case of this investigation it was felt that the value needed to be greater than that suggested in the specification. However, the value selected was somewhat arbitrary. Time and financial constraints prevented further investigation that may be able to refine the selection of a value for nNR_B that would provide a better solution. As a follow on to this work further evaluation may be worthwhile to investigate a range of values that might provide the best solution. Indeed, work may be possible that can suggest an appropriate figure for different cockpit types.

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APPENDICES

APPENDIX A

DESCRIPTION OF AN/AVS-9 NIGHT VISION GOGGLES

Specifications

The AN/AVS-9 NVG is a Type I NVIS device that incorporates 2 IITs and is designed for individual aircrew use in a helmet mounted configuration. The device is shown in Figure 15 and in the donned position in Figure 16. Specification details are contained in Table 7.

Table 7. Selected AN/AVS-9 Specifications

Item	Detail*
Spectral Response	Visible to 900 nm
FOV	40^{o} nominal
Magnification	1 x
Resolution	1.3 cy/mr, minimum (1.36 typical)
Brightness Gain	5500 fL/fL, minimum
Collimation	$\leq 1^{o}$ convergence $\leq 0.3^{o}$ dipvergence/divergence
Interpupillary Adjustment	Independent, 51 to 72 mm total
Vertical Adjustment	25 mm, range
Fore-and-Aft Adjustment	27 mm, range
Tilt Adjustment	10^{o}, range
Objective Lens	EFL 25 mm F/1.23, T/1.35
Objective Lens Filter	Class A, B, C, UK 645 available
Eyepiece Adjustment	+2.0 to -6.0 Diopters
Automatic Breakaway	11 to 15 g
Weight of Binocular	550 grams
Weight of Fixed Wing Mount	250 grams
Operating Temperature Range	-32^{o} C to $+52^{o}$ C

*(ITT Night Vision, 2006)

Figure 15. AN/AVS-9 Night Vision Goggles

Operation

The AN/AVS-9 NVGs are designed to be used by individual aircrew members in a helmet mounted configuration as shown in Figure 16. The device mounts to the operator's helmet by way of a quick release type bracket allowing the NVGs to be easily donned or doffed as the situation dictates. The device is battery operated (using 2 x ½ AA batteries) and can be switched on using a small switch located on the mounting bracket. The device is fully adjustable to suit the needs of all operators that present a wide range of anthropometric measurements and ophthalmologic condition. An example NVG scene is shown in Figure 17.

Figure 16. AN/AVS-9 NVGs in the Donned Position

Figure 17. Sample NVG Scene

During operations the NVGs can be used for any variety of tasks. They are particularly adept for locating targets on the ground especially with the help of an IR illuminator operated by ground personnel. In air-to-air applications, the NVGs are especially useful for locating conventionally lighted aircraft targets or items of interest with detection ranges on the order of 100 NM plus depending on the lighting type. The devices may also be used for night formation flying and to effect safe and effective rendezvous procedures with other friendly aircraft.

The NVGs do have some limitations that must be understood by operators. Most importantly the devices offer only monocular vision. This prohibits the important depth perception cueing to the operator that normal unaided binocular vision provides. Depth perception cueing is limited to monocular cues such as the known size of an object etc. Operators must be aware of this since it can alter perception of closure rates during a rejoin into a night formation flight. Operators must also be aware of the AGC function and how it operates. This is especially true just after the sun has set when the remaining glow of the setting sun forces the AGC to lower the sensitivity of the NVGs to lower intensity light sources. Under these conditions significant contrast reductions can be experienced when attempting to view items on the ground. This necessary limitation must be kept in mind during mission planning.

Use of the device whilst flying is limited to the HUD and external objects. The HUD is focused at infinity and is displayed at a wavelength of approximately 550 nm, thus the displayed image can be viewed sharply on the NVG phosphor screen. Instrument panel lights on the other hand, are close enough to the NVG objective lens that they are significantly out of focus and cannot be satisfactorily viewed through the IIT. By tilting the head back slightly, the operator is easily able to view cockpit instrumentation and displays below the NVGs since the diopter lens is situated approximately 1 to 1 ½ inches from the operator's eye.

APPENDIX B

DESCRIPTION OF THE CF-188 NVIS COCKPIT MODIFICATION

General

The NVIS modification that was carried out on the CF-188 Hornet was a full airframe modification. Every light source on the aircraft was considered for modification in an attempt to make the aircraft fully NVIS compatible. The modification encompassed the internal lighting system as well as all external lights and their respective control systems. This section contains selected excerpts from the EFP that was issued to authorize the testing process and is included for the purpose of background information (Canada. Directorate of Technical Airworthiness, 2004). Since this thesis is only concerned with the internal lighting modifications, the excerpt is limited to that part of the modification. Additionally, the excerpts have been edited to maintain focus on the parts of the modification that pertain to this thesis.

Internal Lighting Modification

The lighting modifications make the internal lighting of the CF-18 cockpit NVIS compatible. Figures 17 identifies the changes to the forward cockpit.

<u>Integrally Illuminated Panels</u>

Integrally Illuminated panels, as shown in Figure 18, on the left and right consoles and instrument panels were replaced with a NVIS GREEN A compatible panel.

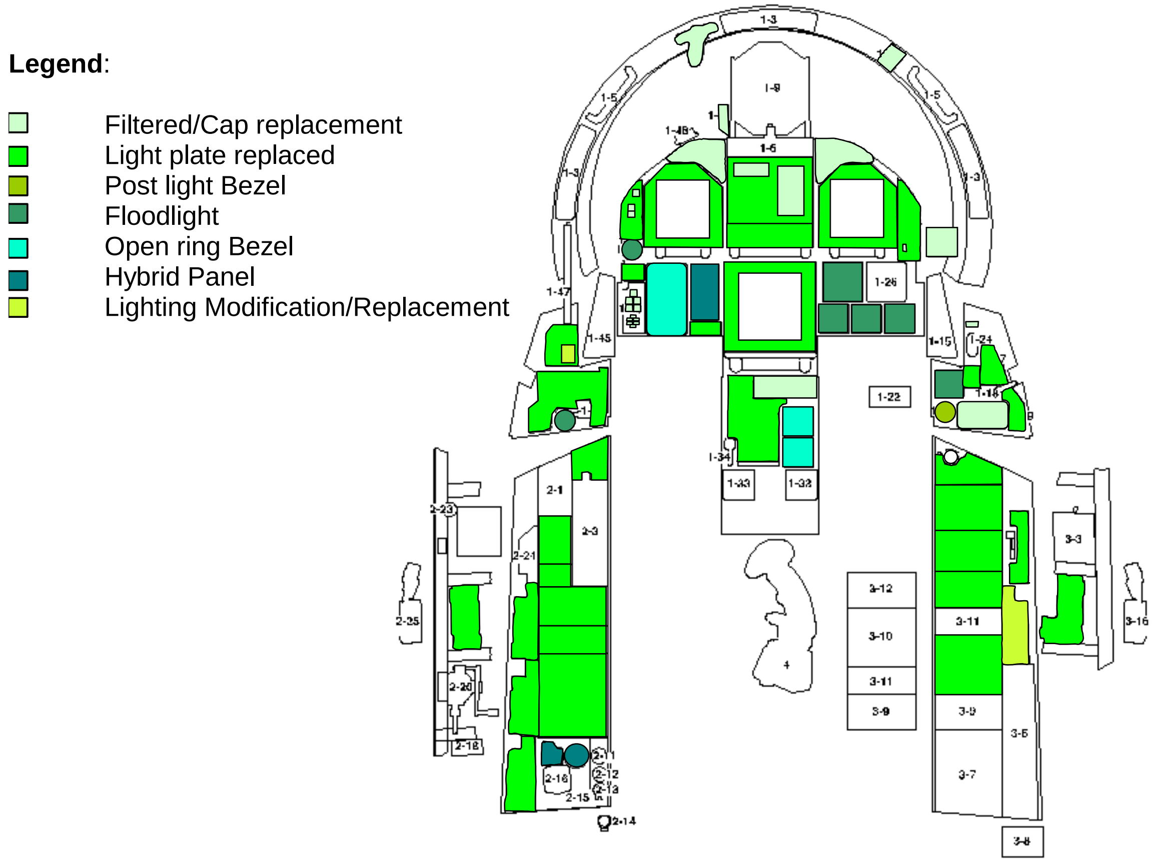

Figure 18. CF-188 Front Cockpit Lighting Modifications

Post Light Bezel

The post light bezel approach is basically used for the gauges and instruments in the cockpit currently using integral back lighting. The back lighting was disabled and an NVIS GREEN A compliant lamp post, was used to directly ligh the instruments. Existing aircraft wiring and circuitry provided the lighting control and power source. Post lights are found on the Oxygen QTY Indicator and the Hydraulic pressure gauge.

Hybrid Panel

The hybrid panel design was used for of any instruments or gauges with markings that had to be lit. In that case the bezel comprised one post light and an integrally illuminated panel portion. This type of modification is found on the Hydraulic brake pressure indicator and Fuel QTY Indicator

Open Ring Bezel

Another design approach for the lighting of instruments was the open ring bezels in which the NVIS GREEN A compliant light, is redirected from an integrally illuminated panel to the instruments using a micro louver. Bezels are used on the aircraft clock, cockpit cabin pressure indicator and the Engine Monitor Indicator.

Annunciator Switch, Cap Replacement or Filter Replacement

In order to make the annunciator light switches NVIS compliant, replacement of switch caps was carried out. This solution is found on all caution, warning, and advisory indicators, pushbutton switches and lights (hook, spin recovery panel, AA and AG switch), master caution panel, and ALR 67 control panel

Interior Lighting Controls

Except for the utility floodlight, UFC display lighting, ALR 67 control panel and AOA indexer lights, all controls for the interior lights are on the interior lights panel on the right console.

Console lighting

All lighting for the left and right consoles, the left vertical panel, and both cockpit circuit-breaker panels is controlled by the CONSOLES knob which provides variable lighting between positions OFF and BRT.

Instrument lighting

All lighting for the instrument panel, UFC background, right vertical panel, Standby instruments floodlights and standby magnetic compass are controlled by the INST PNL knob which provides variable lighting between positions OFF and BRT. The strobe/shoot light is not NVIS compatible; however, the light is disabled when the instrument light knob is in the ON position, at any intensity setting. The standby instrument internal lighting was disabled as part of the NVIS modification. The lighting for this area is now provided by two floodlights mounted in the upper left and right corners of the standby instrument group area, the brightness of these floods is also controlled by the INST PNL knob. When viewing the UFC, the operator must be aware that the new NVIS compatible display conforms to NVIS GREEN B. NVIS GREEN B is used because it increases the daylight readability of the modified instrument.

NOTE: For NVIS operations Instrument Lighting should be selected ON to avoid incompatible strobe/shoot light from blooming[13] NVGs.

[13] The term "blooming" refers to the unbalanced NVG image that occurs when a small, bright, point source of incompatible NVIS light causes the NVG AGC function to engage and significantly degrade the contrast of less bright areas of the image.

Console floodlighting and kneeboard lighting

The eight white incandescent floodlights were replaced with 14 NVIS GREEN LED floodlights. Three console floodlights are above each console, and an instrument panel floodlight is located on either side of the instrument panel. A kneeboard[14] light is installed on the canopy arch. The lights are controlled by the FLOOD knob and FLOOD switch. With the FLOOD switch in the COCKPIT position, the FLOOD knob provides variable floodlighting and kneeboard lighting between positions OFF and BRT. In the CHART position, the FLOOD knob provides variable kneeboard lighting between positions OFF and BRT.

Utility floodlight

The utility light was replaced with an NVIS compatible model. A portable utility floodlight is provided and usually stowed above the right console: an alligator-clip attached to the light may be used to fasten the light at various locations in the cockpit, at the pilot's discretion. The light contains a knob which provides variable lighting from off to bright, and a button which, when pressed, causes the light to come on at full intensity. The light also contains a rotary selector for NVIS White or white lighting.

NOTE: White light selection on utility floodlight is not NVIS compatible.

Emergency instrument light

The emergency floodlight system was not modified with NVIS compatible lighting. A white emergency instrument light, on the right side of the instrument panel,

[14] A "kneeboard" is small board that is strapped to the pilot's thigh. It holds notes and written mission data and provides a scratch pad for the pilot to write notes and clearances on during the flight.

Table 8. Warning and Advisory Lights With Modified NVIS Caps

L/H Threat & Advisory Panel	R/H Threat & Advisory Panel	Front Instrument Panel	Rear Advisory & Threat Panel
L-BLEED	AI	HOOK	L FIRE
R-BLEED	CW	SPIN	R FIRE
L BAR	SAM		APU
FIRE	AAA		L BLEED
	FIRE		R BLEED
	APU		L BAR

comes on to illuminate the standby flight instruments when a double generator or double transformer-rectifier failure occurs. The light comes on whenever a BATT SW caution light comes on. There is no cockpit control for the emergency instrument lighting system.

Colour/illumination issues

With the replacement of the switch caps on the Warning Cautions and Advisories with NVIS compatible caps there is a distinct shift in colour and illumination. This is especially evident when viewing an NVIS red and NVIS yellow, as is the case with the Firelights. The operator must be aware of this colour difference prior to flight. Illumination of all background lit switch caps have been replaced with character lit switch caps. The affected lights are listed in Table 8.

Unmodified equipment

24. The following lights/indicators where not modified by the NVIS project; therefore are not NVIS compatible:

a. AOA Indexer;

b. APU Control Panel light;

c. Lock/Shoot Strobe;

d. White light selection on Utility light;

e. RadAlt Decision Height Warning Light; and

f. Emergency Floods.

APPENDIX C

DESCRIPTION OF THE EVALUATED CANDIDATE FIRE WARNING LIGHT SOLUTIONS

Project Lighting Solutions

Rev-1

The Rev-1 fire lights are shown in Figure 19. These lights where "character lit" whereby an illumination bulb was placed behind a cover that had the appropriate nomenclature etched into a black coating such that the light could escape thereby illuminating the characters. The translucent cover was constructed in a color that would limit the wavelength of the light emitted by the bulb to achieve the nNR_B values stated in chapter IV. The light was a pushbutton type switch designed to be pushed by the pilot should it illuminate in a fire situation thereby activating the fire extinguishing mechanism in the engine bay. It was covered by a spring loaded, hinged guard to prevent inadvertent activation. The two fire lights were located on the upper left and right of the instrument panel with the APU fire light on the upper right.

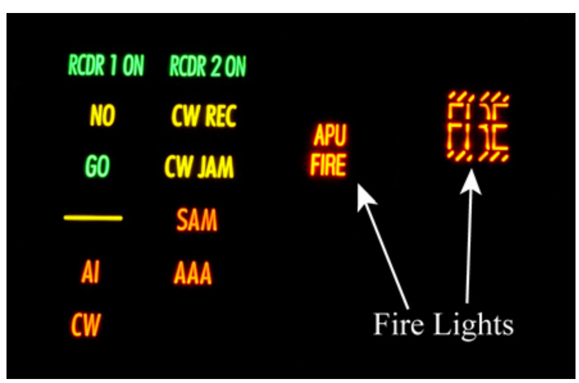

Figure 19. Rev-1 Fire Light Illuminated

Feasibility Study Lights

The feasibility study fire lights are shown in Figure 20. These lights where "back lit" lights whereby an illumination bulb was placed behind a cover that had the appropriate nomenclature painted onto it in a black coating such that the light would provide illumination from behind thereby causing the characters to show up by blocking portions of the light. The translucent cover was constructed in a color that would limit the wavelength of the light emitted by the bulb to achieve the nNR_B values stated in chapter IV. The light itself was a pushbutton type switch designed to be pushed by the pilot should it illuminate in a fire situation thereby activating the fire extinguishing mechanism in the engine bay. The light itself was covered by a spring loaded, hinged guard to prevent inadvertent activation. The two fire lights were located on the upper left and right of the instrument panel with the APU fire light on the upper right.

Figure 20. Feasibility Study Fire Lights

Legacy Lights

There is no available image of the legacy fire lights. The legacy fire lights are identical in appearance and operation to the feasibility study lights. The only difference between the two lighting solutions is that the filter on the legacy fire does not limit the wavelength of the light emitted by the bulb and thus the light is not considered to be NVIS compatible.

Rev-2 and Rev-3

The Rev-2 and Rev-3 fire lights were both very similar in design. The major difference between the two was that the value for nNR_B for the Rev-3 lights was approximately seventy times greater than that of the Rev-2 lights. An illustration of the two lights in the extinguished and illuminated state is shown in Figure 21. The lights were located in the upper right and left corners of the instrument panel with the APU fire light being located in the upper right hand corner.

Figure 21. Illustration of Rev-2 and Rev-3 Fire Warning Lights

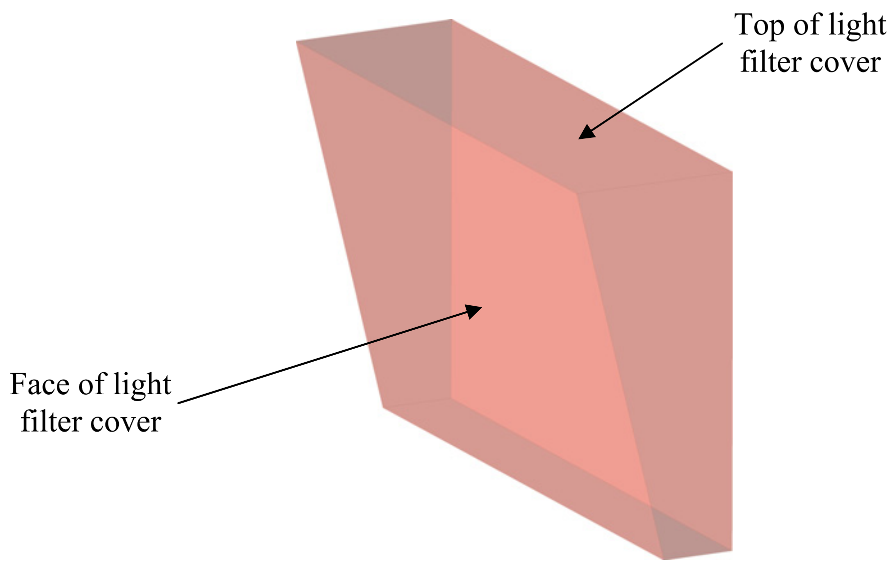

Figure 22. Rev-2 & Rev-3 Prism Design

The lights were of a "character lit" prismatic design. The prism shape is shown in Figure 22. The prism was placed on the front of the light switch and was designed to help eliminate specula sunlight reflections by deflecting reflections down and away from the pilot's eyes. The "character lit" light was designed to permit light to pass through the nomenclature that was etched into the black coating of the light cover thus permitting the etched portion to become illuminated.

APPENDIX D

U.S.A.F. TRI-BAR TO SNELLEN VA CONVERSION TABLE

Table 9. U.S.A.F. 1951 Tri-Bar to Snellen Fraction VA Conversion Table

Tri-Bar Pair		Snellen Fraction
Set	**Pair**	
-2	1	20 / 80
	2	20 / 71
	3	20 / 63
	4	20 / 57
	5	20 / 50
	6	20 / 45
-1	1	20 / 40
	2	20 / 36
	3	20 / 32
	4	20 / 28
	5	20 / 25
	6	20 / 22
0	1	20 / 20
	2	20 / 18
	3	20 / 16
	4	20 / 14
	5	20 / 13
	6	20 / 11
1	1	20 / 10
	2	20 / 9
	3	20 / 8
	4	20 / 7
	5	20 / 6
	6	20 / 6

VITA

Andrew John Soundy was born in Folkestone, England on November 16, 1965. He completed the majority of his high school education in England. At the age of 16 he moved with his family to Toronto, ON Canada where he completed his high school education graduating in 1983.

In 1986 he was admitted to Royal Roads Military College in Victoria, BC Canada. He transferred to the Royal Military College of Canada in Kingston, ON Canada in 1988, graduating in 1990 with first class honors having been granted the degree Bachelor of Engineering, Electrical Engineering. Upon graduation, Andrew commenced Canadian Forces pilot training at CFB Moose Jaw, SK Canada graduating as a fully qualified pilot in 1991. After completing basic pilot training Andrew was trained as a fighter pilot and qualified to mission ready status on the CF-18 Hornet. He flew two operational tours on the Hornet, one with 425 Tactical Fighter Squadron in Bagotville, QU Canada, and one as an exchange pilot with the U.S.M.C. at MAG-31 in Beaufort, SC.

In 1999 Andrew was selected to attend the United States Naval Test Pilot School at NAS Patuxent River, MD. He completed the course as the top graduate of class 117 in June 2000. His first assignment as a test pilot was as an exchange officer with the U.S.A.F. at the 416th Flight Test Squadron at Edwards AFB, CA where he flew all models and blocks of the F-16 Fighting Falcon. He returned to Canada in 2002 and spent the next three years test flying the CF-18 at the Aeronautical Engineering Test Establishment in Cold Lake, AB Canada.

Andrew is a graduate of the Canadian Forces Command and Staff Course, completing his studies at the Canadian Forces College, Toronto, ON Canada in 2006 with a course rating of outstanding. He is currently employed as a Canadian Forces Air Liaison Officer to U.S.A.F. Air Combat Command headquarters at Langley AFB, VA.