Genco, L. V. (1985). Night vision support devices human engineering integration. *AGARD, Visual Protection and Enhancement* (pp. 6-1 through 6-8). (NTIS No. AGARD-CP-379)

NIGHT VISION SUPPORT DEVICES HUMAN ENGINEERING INTEGRATION

Louis V. Genco, LtCol USAF
Air Force Aerospace Medical Research Laboratory
Wright Patterson AFB, OH 45433-6573

SUMMARY

Although Night Vision Goggles (NVGs) extend the luminance range over which we can use our vision, current AN/PVS systems require special cockpit lighting to be fully effective, reduce visual depth of field and diminish the field of view. All three of these factors are extremely important to pilots performing night operations. This paper describes the results of several operationally oriented efforts conducted by the United States Air Force Aerospace Medical Research Laboratory's Human Engineering Division to improve visual performance, cockpit lighting, and flight information transfer in conjunction with the use of night vision goggles. The efforts include an operational definition of NVG compatible lighting, a recommended approach to improving depth of focus, an attempt to expand field of view, and a description of a NVG HUD using optically injected flight data. All efforts center around using or modifying current AN/PVS NVGs used by US forces.

VISUAL PERFORMANCE THROUGH NVGS

Night vision enhancement devices appear to be gaining wide acceptance among both civil and military organizations as means to improve visual perception under conditions of low luminance. The new devices are not merely light amplifiers (light being defined as that portion of the electromagnetic spectrum to which our eyes are sensitive), but extend our capability to see into the near infrared. Because of this differential sensitivity of our eyes and night vision devices, both lighting engineers and night vision device users must be aware of the possible degradations in performance in either the unaided or enhanced visual systems caused by inappropriate lighting schemes. In many cases, inappropriate lighting may cause visual performance through night vision devices to be less than that experienced without the devices in place.

Although the human eye is sensitive to electromagnetic radiation from about 380 nm to about 780 nm, it is not equally sensitive to all wavelengths of light. During daylight or photopic vision, our retinas are maximally sensitive to light whose wavelength is about 555 nm (a yellow-green). During night, or scotopic vision, our retinas are maximally sensitive to light whose wavelength approaches 505 nm (a blue-green). Figure 1 shows the relative spectral and energy sensitivities of the photopic and scotopic visual systems.

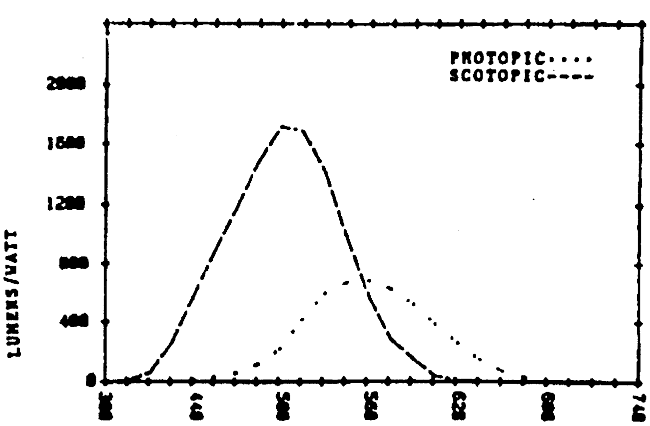

FIGURE I
ABSOLUTE SPECTRAL AND ENERGY SENSITIVITIES OF THE UNAIDED EYE

The dynamic range of the photopic visual system is about 10^8 - 10 ML, and the dynamic range of the scotopic system is about 1- 10^{-6} ML. Although our eyes are very sensitive to light when fully dark adapted (under ideal conditions we can see a candle at a distance of about one mile), their resolution acuity is very low. At best, the scotopic visual system's resolution is about 20/200, and exhibits a central scotoma or blind spot. In other words, small objects will disappear when looked at directly.

First generation devices were photomultipliers that were sensitive to a spectral distribution similar to our eyes. They would amplify what visible light was available, and present the information on a monochromatic display. Since the display luminance was high enough to activate the photopic visual system, the limiting factor in resolution was the optoelectronics in the device rather than the eye.

The visual environment at night is relatively poor in visible wavelength energy, but remains relatively rich in longer wavelength (infrared) energy. Passive devices which used these infrared wavelengths could then rely on a statistically larger number of photons to activate the systems and improve resolution. The US Army's AN/PVS 5A second generation night vision goggles (GEN II NVGs) maintained sensitivity to the visible wavelengths, and extended their sensitivity to the near infrared wavelengths. This meant that the second generation devices could not only "see" light whose amplitude was normally too low for our unaided eyes to perceive, but they could also "see" wavelengths to which our retinas were insensitive, and improve resolution above that given by first generation systems. Figure 2 shows relative spectral sensitivities of the human eye and GEN II NVGs. It also shows the relative amounts of radiant energy available at night.

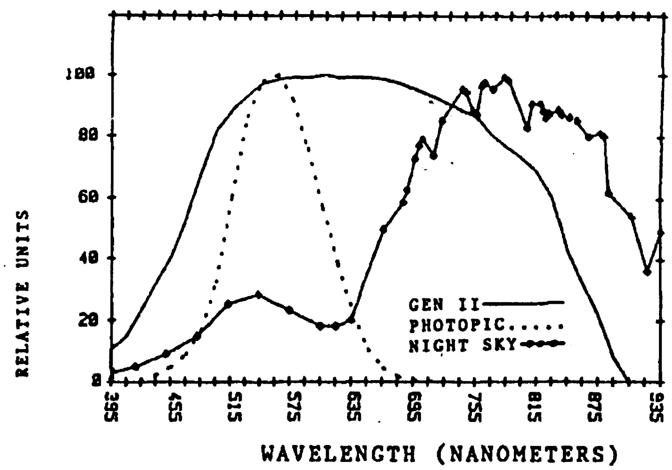

FIGURE 2
RELATIVE SPECTRAL SENSITIVITIES
OF EYE TO GEN II NVG

Scenes viewed through GEN II NVGs are perceived as shades of green because of the phosphor characteristics of the system. The output luminance of the NVGs is sufficient to activate the photopic visual system, but resolution is still limited by the NVGs rather than the eye. Typical visual acuities of individuals wearing operational units under typical night conditions range from 20/80 to 20/50. The unaided daytime visual acuities of these people are 20/20 or better. In addition, the instantaneous binocular field of view (BFOV) is limited to 40° rather than the 180° "unrestricted" field of view. Because of optical inconsistencies in the goggles, stereopsis (one component of depth perception) is poorer than expected for photopic vision, but equal to or better than that experienced with scotopic vision. Table 1 is a summary of various visual thresholds of the unaided eye and the visual system including NVGs.

Table 1

Comparison of Photopic, Scotopic, and NVG-Aided Vision

	Photopic System	Scotopic System	Eye + NVGs
Dynamic Range	$10^8 - 10$ ML	$1 - 10^{-6}$ ML	$10^{+8} - 10^{-8}$ ML
Receptor (Eye)	Cones	Rods	Rods & Cones
System Resolution	Better than 1 arc-min	10 arc-min	2-3 arc-min(NVG)
Spectral Sensitivity	350 - 700 NM	350 - 700 NM	AN/PVS-5: **** AN/PVS-6: ****
Max Spectral Sensitivity	555 NM	505 NM	AN/PVS-5: **** AN/PVS-6: ****
Perceived Spectral Output	Colors	Greys	Greens
Field of View	~ 180°	~ 180°	40°
Max Retinal Sensitivity	0° ± 2.5° (disc)	20°(annulus)	2.5° (disc)
Dark Adaptation Time (full)	10 minutes	30 minutes	Seconds
Dark Adaptation Time (flash)	Seconds	Seconds	Seconds
Dark Adaptation Time (failure)	-	-	Max 2 Minutes

AN/PVS 6 third-generation night vision goggles (GEN III NVGs) have reduced sensitivity to visible wavelengths, and greater sensitivity to longer wavelengths. The GEN III NVG output is also "brighter" than that of the GEN II, insuring the retina is adapted to a photopic level while viewing most scenes through the NVGs. Improvements in the optical system have also contributed to improvements in visual resolution while wearing the goggles, but considering wide variations in both the test method and the goggles themselves, best acuities appear to be in the range of 20/50 to 20/40. The field of view is still limited to 40°, and stereoacuity remains moderately good.

As we gained experience with NVGs in operational environments, several critical human engineering factors became apparent: cockpit (instrument, switch and display) lighting must be compatible with both the NVGs and the unaided eye if both are to be used to their fullest capability; the NVGs could be modified to improve field of view and display characteristics; refocussing from outside the cockpit to see instruments was a problem; new helmet mountings needed to be designed to better distribute the weight; and future NVG design must consider safety and ejection factors.

NVG COMPATIBLE LIGHTING

In order for NVGs to be most effective, the cockpit lighting must be optimized for the NVG's spectral sensitivity. Even low amounts of red and IR wavelengths generated within the cockpit can significantly reduce the goggles' sensitivity to the outside scene. Several vendors are now producing "NVG compatible" lights, even though there is no generally accepted measure of compatibility. The most promising products appear to be those that drastically reduce or eliminate emissions correspoinding to visible red and longer wavelengths, however the absence of red warning lamps may be of some concern to traditional cockpit lighting engineers.

Our definintion of "NVG compatibility" contains two general criteria: 1) the lights will not degrade vision through the NVGs for specified lighting positions or configurations, and 2) the lights will allow good vision of instruments or other objects for the unaided eye. We include not only instrument and panel lights in this definition, but CRT and other displays.

Many users found that normal incandescent sources which were used to provide in-cockpit illumination for the unaided eye would emit too much infrared energy, and cause the NVG to lose sensitivity to out-of-cockpit scenes (because of activation of the automatic gain control). Many filtering systems, electroluminescent lighting schemes, and light emitting diode schemes were investigated; all of which were intended to reduce the emitted IR energy, and maintain sensitivity of the goggles.

We have found it helpful to describe at least three categories of cockpit lighting configurations, and have begun to establish compatibility ratios for most "NVG compatible sources" for each condition. Category 1 includes lights in the direct field of view of the goggles, category 2 includes light reflected from the windscreen or other object into the goggles, and category 3 includes "light pollution" from other sources. When viewing outside scenes, lights which are almost always in the direct field of view of the NVGs should not be considered to have the same effect as light sources normally well out of the NVG field of view.

We have developed a preliminary Compatibility Ratio (CR) that takes into consideration properties of both the unaided eye and the NVGs. This Compatibility Ratio may be used for any lighting configuration, type or placement, and will predict the relative effects of various vendors' products on visual and NVG performance. Essentially, CR is the ratio of the photopic eye rerponse for a particular wavelength to the ANVIS sensitivity to the same wavelength.

Compatibility Ratio may be expressed mathematically as follows:

$$CR = \frac{\int_{400}^{700} V_\lambda \; N \; d_\lambda}{\int_{400}^{1000} G_R \; N \; d_\lambda}$$

Where:

V_λ = Relative photopic eye response for CIE 1931 standard observer

N = Relative spectral radiance for a particular light source (Watts/cm^2 Sr nm)

G_R = Relative ANVIS spectral response as measured or specified by manufacturer or JLC Ad Hoc Committee

Appropriate Compatibility Ratio limits are now being found by empirical determination for a subset of typical cockpit illuminators and categories. Spectroradiometric measurements of other illuminants will then allow ranking or compatibility comparisons of many cockpit lighting types and sources without the necessity of complex simulator devices. The CR will also provide suitable wavelength mixture information to lamp designers.

We are also in the process of defining spectral loci for acceptable NVG compatible cockpit lighting. Assuming the pilot will be able to see various instrument and cockpit indicator lights both with and without the NVGs, the problems of appropriate color coding, equality of hue and equality of luminance for either unaided or aided vision are added to the list of concerns for the illumination engineer. Care must be taken that warning and caution lights are sufficiently different from "normal" illuminants to avoid confusion. Historically, this has been accomplished via color coding the former lights red or yellow, but since these longer wavelengths are not compatible with NVG usage, the choice of spectral components is severely restricted.

NVGS AND VIDEO DISPLAYS

Initial tests indicate color video displays will have to be modified to reduce long wavelength emissions. Essentially, this means eliminating or significantly reducing the output of the red gun, with resultant degradation in visible color separation for the display graphics or symbology. In addition, displays using P-43 or similar phosphors will have to be filtered to reduce the normally tiny long wavelength "bump" on the emission curve. If this is not done, the display will cause the NVGs to lose sensitivity at brightness levels just barely sufficient for comfortable unaided vision.

One possible use of passive NVGs is in conjunction with active FLIR or other systems whose information is presented on a Heads Up Display (HUD). Since the HUD imagery is at optical infinity, refocussing the NVGs is eliminated. However, holographic or diffractive HUD combining glasses are tuned to reflect only the narrow green band of the P-43 phosphor. The imagery generated by these HUDs appears dimmer with AN/PVS 6 goggles than without! The reason for this apparent anomaly is the presence of a minus-blue objective lens coating, which prevents much of the green band from entering the NVGs.

DEPTH OF FOCUS PROBLEMS AND SOLUTIONS

The normal eye can accommodate or focus on objects at different optical distances. When we fixate on distant objects, near objects are blurred. When we change focus to the near object, the distant target is blurred. The range of distances over which we can see clearly without refocussing is called the "depth of focus" or "depth of field". Refocussing is accomplished by the action of the ciliary muscles in each of our eyes, changing the shape of the crystalline lens.

When properly adjusted, the ocular lenses of the night vision goggles place the image of the scene near optical infinity for the wearer's eyes. The NVG's objective lenses are then adjusted to focus on the object of regard. Because of their small f-number, there is very little depth of focus for NVGs. If a pilot had his system focussed for out-of-cockpit viewing, he would be unable to clearly see legends or instruments within the cockpit without manually refocussing each tube. After reading his instruments, he must then refocus for clear distance viewing.

The AN/PVS 6 goggles were provided with an Aviator's Night VIsion System (ANVIS) mount, which allowed the pilot to look under the tubes to see his instruments. This feature attempted to eliminate the refocussing problem encountered with the AN/PVS 5 mounts, which were designed for ground use. Unfortunately, the ANVIS mount moved the center of gravity of the goggles farther from the head, and emphasized the problem of maintaining lighting compatibility for both the goggles and the unaided eyes at the same time. In addition, when the pilot wanted to see instruments near the top of his glare shield, the pilot needed to move his head in an uncomfortable manner to move the goggle tubes out of his field of view. Several other NVG manufacturers produced different systems to reduce the near vision problem, such as the Marconi Cats Eye, and the FJW Industries See-Through Night Vision Goggle (SNVS).

Another answer to the refocusing problem is addressed by shared-aperture optics. The concept of shared-aperture optics is similar to that of pinhole optics, in which light is imaged on a surface without the use of lenses. The shared-aperture concept is similar in that the objective lenses of the NVGs are coated with a minus-blue filter, effectively blocking short visible wavelengths of light. If cockpit lights are filtered or otherwise caused to emit only short wavelengths, these lights will not be seen when looking through the goggles. Now envision a small aperture, similar to that in a pinhole camera, in the minus blue coating. The relatively high energy, short-wavelength instrument light can pass through this aperture, and form a clear image in the NVGs. The large area around the aperture acts as a relatively low f-number optical system to the outside scene, which is rich in long wavelengths. With appropriate shared apertures, and with the system focussed for infinity, the pilot can see both the outside world and his instruments with relatively normal head and eye motions. Figure 4 diagrams the optical concept of shared apertures, which can be incorporated into present AN/PVS systems.

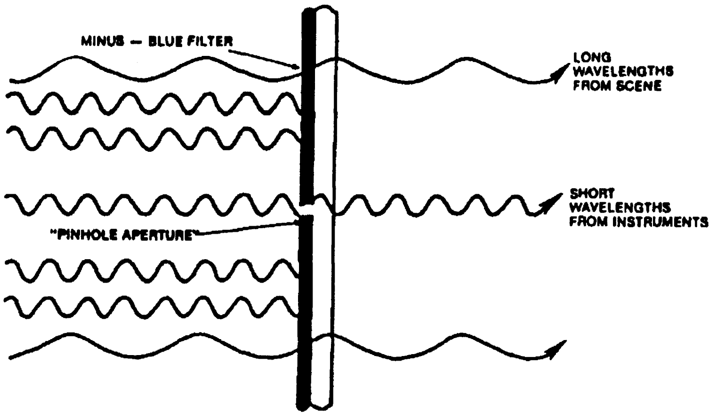

FIGURE 4
OPTICAL CONCEPTS OF SHARED APERTURES

One disadvantage of shared aperture optics is the critical selection of wavelengths suitable for in-cockpit illumination. These wavelengths must be almost totally blocked by the filter coating on the objective lens, thus significantly reducing the number of available illuminant choices.

FIXATION POINT PROBLEMS AND SOLUTION

Unfortunately, with any of the above methods of allowing vision of both the exterior scene and cockpit instrumentation, the pilot is still required to change his visual point of regard from outside to inside views; requiring changes in accommodation (for conventional aperture systems), light adaptation, and fixation posture. While his visual system is busy with one scene, important changes could be taking place in the other. Since NVGs are typically used at very low altitudes, normal aircraft velocities cause high rates of approach, and concurrent rapid changes in visual scene, which may degrade safety.

Scientists at AFAMRL approached the problem of seeing both the outside scene and instrument display by electronically and optically injecting critical flight instrument readings into the optical path of the NVGs. Now, the pilot need adjust his NVG's focus only once -- for distant viewing, and the flight data would also be seen near optical infinity, in the same field of regard as the outside scene. In effect, we created a Heads Up Display (HUD) for the NVGs, so we named it the AFAMRL NVG HUD.

Before using the NVG HUD, the visual duties of crew members of night flying aircraft were partitioned -- some tasked to look outside and others tasked to look only at instruments of various types. The pilot was to look outside the cockpit, while the co-pilot was to look at the critical instruments. Both the radar operator and copilot reported to the pilot verbally over the intercom. All crew members who were to look outside the cockpit wore night vision goggles, and the cockpit lighting was suitably modified to least interfere with the NVGs.

Since the development of the AFAMRL NVG HUD, the visual tasks of the crew can be partitioned in a more normal (i.e. more similar to daylight flying) fashion. The pilot's visual abilities are actually enhanced in that he can now see both the outside scene and flight data at the same time, without refocusing either his eyes or the NVGs. In fact, he need not change his visual regard from any exterior scene of interest; his flight data are projected to appear near the point at which he is looking.

The aircraft for which the NVG HUD was originally designed were not equipped with conventional HUDs, but displayed information on both video displays and round-dial instruments located on a conventional instrument panel. AFAMRL engineers were able to sample data on the computer bus serving the instruments, and use these data to generate a display on a small CRT. Several interactive studies were performed by AFAMRL and MAC to determine the optimum display format and symbology to effectively portray data values.

The CRT display was then coupled to a coherent fiber optics bundle, which was passed to the pilot's helmet. The output of the bundle was collimated and reflected from a beamsplitter or combining glass mounted on the NVG barrel, into the optical path of the

NVGs. In this fashion, the wearer of the NVGs could see the outside scene with both eyes, and the flight data image with one eye.

The brightness of the displayed data can be dimmed by the pilot, so he can "look through" the graphics at the outside scene, using binocular vision. As the need for critical flight data increases, he can increase the relative brightness of the graphics, so he can easily perceive the data with one eye. Since the other eye continually maintains a view of the out-of-cockpit scene, the visual system superimposes the imagery created on the face of the CRT over the outside scene. Since there is a great difference in appearance of the images, there is no retinal rivalry effect, and both the outside scene and the flight data are seen constantly. There have been no reports of the Pulfrich phenomenon while using the system, and no unusual lighting compatibility criteria need be addressed.

FIELD OF VIEW IMPROVEMENTS

Both the AN/PVS 5 and AN/PVS 6 NVGs restrict the wearer's instantaneous binocular field of view to a 40° circle. In order to carry on any visual search pattern, NVG wearers must increase the amount of head and neck motion to cover the same area previously covered by relatively simple eye movements alone. This increased head movement, combined with the weight distribution of the NVGs contributes greatly to neck muscle fatigue. Optically increasing the field of view of the NVGs results in a reduction of resolution. The pilot might see more in his instantaneous field of view, but what he does see will be less distinct.

One possible method of improving the horizontal field of view is "toeing-in" the NVG tubes. Since the NVGs have a magnification factor of 1, moving the tubes from their parallel position will have no effect on the positions of the eyes' lines of sight. Some time ago, AFAMRL produced a prototype NVG arrangement with the tubes "toed-in" 10° each. The result was an instantaneous field of view of 60°, consisting of a binocular overlapping field of view of 20°, and two monocular fields of view, each of 20° (See figure 5). All images in the instantaneous field of view maintain their correct relationships to all other images, and many pilots who tried the goggles were unaware of the presence of two monocular fields until told to alternate closing their eyes. The toe-in concept is not a new one ... it was patented in the US several years ago and is also demonstrated with Marconi's Cats Eye NVGs.

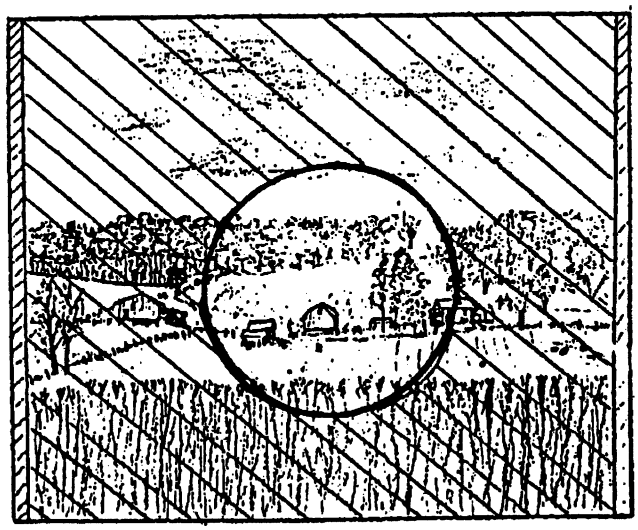

FIGURE 5A
CURRENT 40° FOV

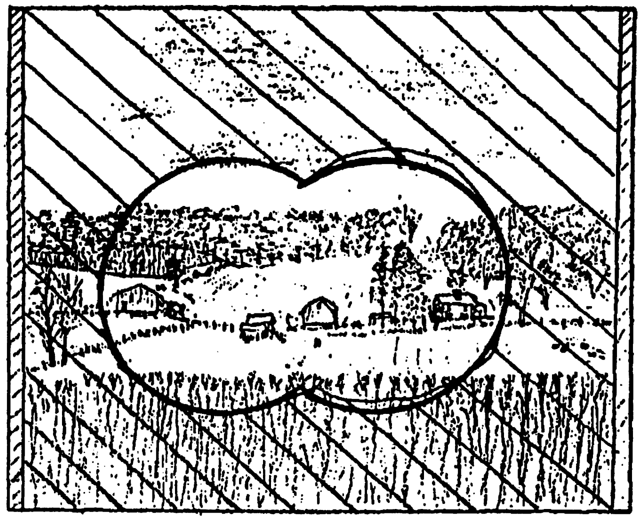

FIGURE 5B
AMRL MODIFIED FOV

FUTURE CONCEPTS

As display technology improves, and computer enhanced imagery matures, it is possible that the pilot of the future need not depend soley on his unaided vision while flying at night or under conditions of poor visibility. We see the early stages of new visual applications in the acceptance of NVGs, HUDs and FLIRs. The concept of providing enhanced imagery to the pilot is not new, but the methods to do this are rapidly evolving. AFAMRL is at the forefront of this technology with its state of the art Visually Coupled Airbourne Systems Simulator (VCASS), which allows the pilot to take advantage of new sensor technology by displaying various imagery on his helmet visor. Systems control, sensor pointing and device switching are performed with normal head and eye movements, providing a wide binocular field of view, with computer enhanced imagery, color and symbology. Artificially induced stereo cues add a new dimension to spatial sense.

The use of night vision enhancement devices appears to be growing in acceptance. Performance with these devices will be further aided by assuring appropriate human engineering factors are considered both in their design and application. It is not necessary to wait for next-generation improvements to become available in order to have an effective night vision system useable by aircraft pilots. NVG modifications and ancillary devices made and planned by AFAMRL and other organizations can be applied to today's second and third generation products.