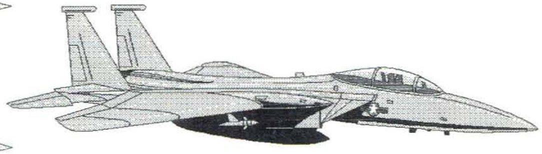

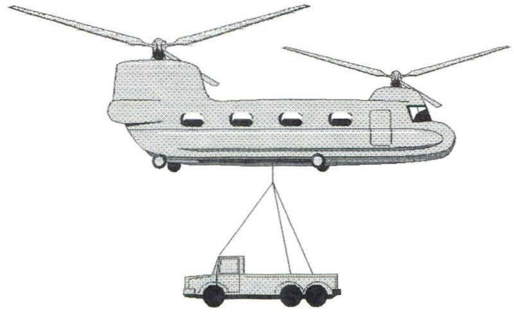

# The Degree to which Night Vision Goggles Meet the Night Vision Needs of Military Pilots

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Military strategists have long sought the ability to exploit the night in military operations through avoiding detection, defeating optically aimed weapons, and denying the enemy an opportunity to rest and resupply its troops (2). Current night vision imaging devices such as Forward Looking Infrared (FLIR) and Night Vision Goggles (NVGs) have revolutionized military aviation through providing the means by which military operations are able to take place at night, even under very low luminance levels. Colonel William Berkley, USAF, stresses their importance in stating, "the total impact of night vision devices has probably been greater than that of any technological advance since the development of the jet engine" (2). This paper reviews night vision goggle technology and will specifically focus on the performance and use of NVGs by United States Air Force cargo pilots and their concerns regarding the current state of NVG technology. Night Vision Goggles are an essential tool to today's military pilot, but further advances in NVG technology and training must be made.

Being able to see in the dark when your enemy cannot gives one a great advantage, and "fighting in the dark with night vision equipment is as close as it gets to being 'invisible' to the enemy" (4). Unaided visual acuity under full moonlight is approximately 20/100 and 20/400 under starlight (6). This low level of acuity is due to the fact that at levels of low illumination ($10^{-6}$ to $10^{-3}$ mL) the rods are responsible for vision (scotopic vision). At higher levels of illumination (1 to $10^{+4}$ mL) the cones are responsible for vision (photopic vision). The dimmest light which rods can detect is about $10^{-6}$ millilamberts (mL), which is equivalent to ambient conditions of an overcast night with no moonlight, and the dimmest light which cones can detect is about $10^{-3}$ millilamberts which is roughly equivalent to a night with fifty percent moonlight (14). At intermediate levels of illumination ($10^{-3}$ to 1mL) both rods and cones are responsible for vision (mesopic vision). Visual acuity of 20/20 cannot be sustained below about 1 mL, so visual acuity under average night-time conditions is reduced (14). In addition to decreased visual acuity under scotopic levels of illumination, a blind spot corresponding to the location of the foveola also exists in the central one degree of the visual field for luminance levels of $10^{-3}$ mL and below (14). While this central scotoma may seem insignificant in terms of field of view, it correlates to the size of a toggle switch at 3 feet, a fighter plane only 1,000 feet away and a bomber at a distance of 3,000 feet (14).

Given the above facts concerning unaided night vision, it is apparent that a device must be used to transform the low luminance levels of the night-time sky into higher luminance levels at which our visual system is capable of resolving finer detail. Two such devices are Forward Looking Infrared (FLIR) and Night Vision Goggles (NVGs).

Forward Looking Infrared devices are aircraft-mounted thermal-imaging systems which do not rely on visible light, and can thus function during periods of total darkness and heavy smoke (4). These devices collect heat, which is infrared radiation, and are sensitive to temperature differences of only 0.1°C (4). The visual image generated by FLIR devices shows differences in thermal temperatures of objects and is displayed on high-resolution CRTs in the cockpit, as well as on the pilot's head-up display (HUD) (4). The FLIR field of view is usually twenty to thirty degrees (4). FLIR devices differ from NVGs in that they can see through fog, smoke, brownout, haze, and clouds while NVGs cannot (14).

Night Vision Goggles are devices which detect low levels of visible and short wavelength infrared radiation and photoelectrically amplify and convert it into visible light which is emitted from a phosphor-coated image intensifier (23). Thus NVGs are capable of transforming light from scotopic conditions into mesopic conditions (13). Most NVGs are helmet-mounted and look like binoculars, and have unity magnification (14). "The U.S. Air Force currently uses NVGs in both helicopters and fixed-wing aircraft" (14).

The image-intensifier tubes of Night Vision Goggles are made up of three main parts: photocathode, amplifier, and phosphor screen (4). Incoming light is focused onto the photocathode by an objective lens. The photons of light are converted into electrical energy in the form of electrons by the photocathode (4). Microchannel plates powered by a high voltage then amplify the number of electrons incident upon it and guide the electrons onto the phosphor screen producing an intensified monochromatic virtual image (14). The image resembles the image of a black and white television image, except that the NVG image is in shades of green with a peak at about 530 nm (14). Focus adjustments are made using the individual eyepieces (14). The amount of light amplification is referred to as the gain of the device (14). The typical gain of an NVG is about 2,000 for ANVIS NVG as compared to 800 for AN/PVS-5 NVG (4). Current NVGs have an adaptive gain control mechanism which limits the number of electrons that the microchannel conducts when bright objects such as flares are viewed (4).

The earliest image intensifier NVGs were used in Vietnam (14). A "first generation" (Gen I) hand-held image intensification device, the Starlight Scope, saw limited aviation service in Vietnam (2). In the early 1970's, second generation (Gen II) binocular head mounted devices became available and were intended to be used primarily by truck and tank drivers (2). These second generation NVGs were first used for aviation by U.S. Air Force helicopter pilots, and later by U.S. Army helicopter pilots in the early 1970's (14).

The AN/PVS-5 (Army and Navy/Personal Vision System) is the most commonly used II-Gen NVG today (14). There are three versions of the PVS-5 (a, b, and c) (22). The first version had a bulky padded surface that rested against the face. This made it difficult to look around the NVG, and so later versions were modified to permit the pilot to look around the NVG at the flight instruments (22). The best possible resolution obtained with this NVG is about 20/50, and the widest field of view is a circular forty degrees (14,22). The PVS-5 is sensitive to light from about 400 nm to 900 nm (22).

Third generation (Gen III) NVGs were designed specifically for helicopter pilots and appeared in the early 1980's (2). These NVGs have the advantages of better resolution and greater sensitivity to lower light levels, and are the current mainstay for NVG military aviation (2). There are many different versions of III-Gen NVGs, but the most commonly used III-Gen NVG is ANVIS (Aviator's Night Vision Imaging System) (14). It is, "the most advanced image intensifying system currently available and is widely used in military aviation" (6). Limitations for ANVIS include a circular forty degree field of view and resolution of about 20/40 under full moonlight illumination ($10^{-2}$ mL) and 20/63 under clear starlight illumination ($10^{-4}$ mL) (5,6). ANVIS is sensitive to light from about 625 nm to a little over 900 nm (14). "The single most important technical feature of the ANVIS is its improved low-light performance" (14).

Significant differences exist between the PVS-5 NVG and ANVIS NVG. ANVIS is about four to five times more sensitive in low-light conditions than the PVS-5 (22). ANVIS also has a filter rejecting wavelengths below about 625 nm, which makes it more compatible with blue-green cockpit lighting (15). Another difference is the useful life of the NVG. PVS-5 NVGs have a useful life of about 2,000 to 4,000 hours, and their useful life decreases with hours of usage as the tubes signal-to-noise ratio decreases (15). Reigler, et. al., did a study which showed that increases in signal-to-noise ratio in image intensifier tubes results in better visual acuity at both quarter moon and starlight conditions, and that signal-to-noise ratio has its, "greatest impact on visual performance under conditions of lower illumination" (19). In contrast, ANVIS NVGs provide a relatively constant performance and last about 7,500 hours before falling off rapidly (15). Furthermore, ANVIS weighs about 550 grams as compared to the heavier PVS-5 which weighs about 880 grams (22).

As discussed above, current NVGs can be a tremendous aid to night-time military operations. They have a field of view of about forty degrees, and the best possible visual acuity through the best NVG under optimal illumination is around 20/40 (7,21). The normal unaided field of view is 200 degrees horizontally and 120 degrees vertically (21). Although NVGs do drastically enhance one's vision at night, they do not turn night into day (14).

Visual performance through NVGs in limited by technology in three major ways: image quality, field of view, and depth perception. Image quality is the first, as it affects the other two. The visual acuity level of 20/40 for ANVIS listed above is usually only reached indoors under artificial conditions with a light level of about eighty percent moonlight (14,20). Visual acuity with NVGs decreases at lower levels of illumination. One field study has shown that, "under ambient starlight conditions, mean visual acuities for high contrast eye charts were reduced to less than 20/100 with AN/PVS-5 and less than 20/80 with ANVIS (14).

Visual acuity with NVGs has been measured in a number of ways. One such way is through the use of the NVG Resolution Chart, which has nine square-wave grating patterns with varying spatial frequencies from 20/35 to 20/100 (20). The chart can be rotated to four different orientations to prevent memorization (20). The results of one study showed that NVG visual acuity measured with a Snellen Chart is higher (20/38) than when measured with the NVG Resolution Chart (20/45) for ANVIS (20). Similar results were obtained with the PVS-5 NVG (20). Dr. Jeff Rabin, an Army NVG researcher, has also demonstrated that flicker detection, vernier acuity, and contrast sensitivity are all decreased with NVGs as well (16,17,18). The resolving power of NVGs decreases at lower light levels because the background noise increases in proportion to the signal, thus decreasing the signal-to-noise ratio.

In addition to this technical limitation to visual acuity through NVGs, DeVilbiss, et. al., showed that, "when experienced NVG aircrew members routinely adjust the goggles during preflight using their 'usual' method of adjustment, the average level of goggle performance under ideal conditions is less than optimal, averaging between 20/50 and 20/55" (8). However, when the NVG Resolution Chart was provided for use in preflight adjustment, the visual acuity levels increased to between 20/45 and 20/50 (8).

The reason for the less than optimal image quality provided by current NVGs has to do with the simple geometric model of the inverse relationship between resolution and field of view

(R=N/2X) (12). In this equation, R is resolution in cycles per degree, N is the number of pixels across the display, and X is the field of view in degrees (12). As visual acuity improves, field of view decreases. Normal visual acuity for the human eye is approximately 20/20 (one minute of arc) for high contrast, brightly lit targets (21). By the above equation, ANVIS, which is capable of yielding 20/40 visual acuity with a forty degree field of view, must have about 1,200 pixels. If an image source consisted of 1200 by 1200 pixels, and each pixel on the display subtended an angle of one minute of arc, the NVG would be capable of generating 20/20 acuity but the angular subtense (field of view) of the entire display would be small at only twenty degrees. As such, a balance must be reached between field of view and resolution for a fixed number of pixels.

The number of pixels per unit area may be a limiting factor here. Theoretically, you should be able to produce an image intensifier tube capable of both better resolution and field of view by increasing the number of pixels per unit area. In order to double both the best current resolution and field of view (resulting in 20/20 and an eighty degree field of view), you would need 4800 pixels on the NVG image display, which is about four times the number of pixels now in the best NVG.

"Field of view with the NVG is a theoretical value; it is based on one's ability to obtain minimal eye relief and proper eye positioning within the designed eye positions of the NVG optics" (14). As with other telescopes, in order to obtain optimal field of view, the exit pupil of the goggle must coincide with the entrance pupil of the eye. "To a pilot, the most apparent disadvantage of night goggles is a narrowing of the field of view from a normal 200 degree horizontal field of view to 40 degrees" (15). The image intensifier tubes have one hundred percent overlap, so the forty degree field of view is a binocular field of view (14). The NVG field of view can be made slightly larger by making the field of view of each image intensifier tube only partially overlap (22). One study has shown that, "an eighty percent overlap binocular NVG may be a good compromise between the need for larger field of view without impacting visual performance" (22). A pilot wearing NVGs must compensate for the decreased field of view by constantly moving his head to scan (15). "Unfortunately, it is difficult for manufacturers to design new NVG with a wider field of view because, as you increase the field of view, the weight and size of the objective and eyepiece lenses increase significantly" (14).

Both stereopsis and monocular clues to depth perception are reduced through NVGs because of the decreased resolution (14). ANVIS normally provides better depth perception than the PVS-5, since it has slightly better resolving capability (14). Both distance and depth perception are significantly decreased with NVG when compared to normal day vision, especially at lower light levels where NVG resolution is reduced even further (3). Most depth perception with NVGs is due to monocular cues such as linear perspective, texture gradient, interposition, size and shape constancy, motion parallax, and relative size (3).

"Studies have shown that the available depth perception cues with NVG are, at best, equivalent to performing these maneuvers with only one eye during the day" (14).

In addition to decreased resolution, field of view, and depth perception at night, pilots are also more susceptible to visual illusions and misperceptions at night. Misperceptions and illusions occur with NVG in all types of military aircraft, but most commonly in helicopters during hover (3). There is a greater tendency for illusions and misperceptions to occur at lower levels of illumination (3). With NVGs, "the image intensification process tends to intensify the illusions as well as the ambient light" (3). "Water is virtually invisible to NVGs unless there is some surface texture present", and reflection of stars by water can cause spatial orientation problems with NVGs (3). Snow, shadowed areas, and areas in which there is little contrast, such as a desert, can cause problems with spatial orientation as well (3). Misperceptions of the horizon, runway lights, and mistaking stars or ground lights for other aircraft can also occur at night (14).

Weather has an affect on the performance of NVGs as, "atmospheric conditions that degrade unaided visual performance will also degrade the performance of NVG" (14). "Optimal NVG performance is obtained on a clear, dry night", while precipitation such as rain or snow and obscurants such as fog, smoke and dust degrade the performance of NVG (14).

Light levels also affect NVG performance. As mentioned above, resolving ability decreases with decreasing levels of ambient illumination. "At light levels below starlight, NVG may lose their operational effectiveness, even though some measurable resolution remains" (14). Conversely, flying toward bright light sources such as city lights or the moon can also degrade the performance of NVGs (14). "The current policy of most military services restricts NVG flights to periods of natural illumination which meet or exceed the lunar conditions of twenty percent moonlight at thirty degrees above the horizon" (14).

Non-compatible aircraft cockpit lighting can decrease NVG performance significantly (3). Low intensity white lights are often used for cockpit lighting. The gain of a NVG is so high that almost any amount of cockpit lighting is too high for NVG function (14). This can make the pilot more susceptible to the illusions and misperceptions discussed above. In order to make cockpit lighting more NVG compatible, a military lighting specification was adopted (Mi-L-85762) which states that the cockpit is to be illuminated with light which is visible to the unaided eye but is invisible to the NVGs (21). Gen-III NVGs such as ANVIS are equipped with a "minus-blue" filter that rejects wavelengths below 625 nm, and blue-green cockpit lighting has been installed in some aircraft (14). Thus, the cockpit lighting in these aircraft is invisible to the NVG and can only be seen when the pilot looks under the NVGs.

Fatigue can also be caused by NVG and can lead to decreased performance (14). Visual fatigue such as asthenopia or eyestrain can be reduced by receiving proper fitting and adjustment training, relaxing accommodation when adjusting NVGs, wearing the proper spectacle or contact lens prescription, and controlling sources of glare (14). Physical fatigue is caused by NVGs because of the added weight to the aircrew helmet, which can significantly shift the center of gravity (14). This results in fatigue and soreness to the neck and shoulder muscles, which affects aircrew performance (14). Physical fatigue can be minimized by balancing the NVGs with a counterweight, strengthening neck muscles, obtaining proper helmet fit, and maintaining good posture (14).

Flying at night with NVGs is dangerous. The pilot is more susceptible to spatial disorientation, misperceptions, and illusions. Furthermore, visual acuity, field of view, and depth perception are reduced. "Accident rates per 100,000 flying hours are greater for NVG missions compared to daytime flying, or even unaided night missions" (14). In these accidents, it has been noted that, "the most common contributing human factor was inexperience" (3). Currently, all Army and some Air Force and Navy aviators are instructed in NVG use (20). In order to standardize NVG training procedures within the U.S. Air Force, a NVG training course was developed (8). It consists of didactic presentations, hands-on goggle familiarization and adjustment procedures, terrain board demonstrations of visual effects and illusions, and videotapes of actual intensified imagery (8). "The single most important phase of training is the NVG fitting, adjustment and preflight assessment" (3). The NVG resolution chart is used in this training for focusing of the NVG and evaluation of NVG visual acuity (8). Night vision goggle training results in better NVG performance among trained aircrew members (8).

In order to, "gather information regarding operational experiences with night vision devices from all Major Commands that use NVGs", a Night Vision Goggles Users' Concerns Survey was conducted (10). The survey addressed the issues of: Demographics of NVG users, NVG training experience, NVG design and usage problems, actual flight experiences with NVGs, and general concerns regarding devices currently being used (10). The format of the survey included analysis of NVG adjustment procedures by crew members, measurement of NVG visual acuity, a questionnaire regarding NVGs, and an in-depth interview with individual crewmembers (10). A training course in preflight adjustment procedures was also conducted (10). The results I will focus on will be from surveys conducted on the aircrew of three common U.S. Air Force cargo aircraft; the C-130E, C-141, and C-5B. I will specifically focus on the responses and concerns of the pilots and co-pilots of these aircraft. These aircraft use ANVIS NVGs (9,10,11).

All three of the above cargo aircraft typically fly NVG missions which last from four to six hours and are at an altitude of 500 to 1,000 feet. Most of the pilots and co-pilots state that while on NVG missions, their NVGs are primarily focused outside of the aircraft. The aircrews of these three aircraft described the best conditions for NVG usage as nights with clear visibility, good weather, and maximum goggle usage of between two to four hours. The worst conditions for NVG usage included clouds, rain, humidity, poor visibility, use of NVG past two to four hours, and, "anything beyond two to three consecutive nights of NVG flight missions" (9,10,11).

The ability of aircrew members to adjust NVGs was evaluated by having them use their typical preflight NVG adjustment procedure. There was no standard target used by a majority of aircrew members when focusing their NVGs. Some of the reported targets which were used included hands, interior walls, ash trays, mirrors in the lavatory, scenery outside the aircraft, pictures on walls, and engine instruments. The distance at which these targets were focused ranged from two feet to optical infinity (9,10,11). Only one crew member, a pilot, reported using an acuity chart to focus his NVGs (9). The average visual acuity obtained by crew members using these focusing targets was between 20/48 and 20/51. The average visual acuity using the same procedures but the NVG Resolution Chart as the target for focusing were higher at between 20/42 and 20/48. In general, NVG visual acuity increased when a standard target (NVG Resolution Chart) was used for focusing. This general trend was true for all crew member positions including pilots and co-pilots, engineers, loadmasters, and navigators (9,10,11).

Crew members who participated in the survey were asked if they had received any formal or informal NVG training. Out of all the pilots, only one had received formal NVG training, but it was in 1978 with the PVS-5 NVG. Therefore, no pilot in these three surveys had received any NVG training with ANVIS NVGs. Fifty percent or less of the pilots indicated that they had received any informal training with NVGs in each of the three surveys. Informal training was defined as basic familiarization and demonstration by someone who was experienced in the use of NVGs. Fifty percent or greater of the pilots of each of the three survey indicated that they had neither received formal nor informal training in the use of NVGs (9,10,11).

Crew members reported a number of symptoms due to the use of NVGs. Common physical symptoms included muscular fatigue, difficulty focusing, drowsiness, and general discomfort. These symptoms were reported to be more prevalent under the worst NVG conditions referred to above. Fatigue generally became more of a noticeable problem when the NVGs were worn for more than two or three hours. Another frequent complaint was a difference in image intensity between different sets of NVGs and focusing differences between individual tubes (9,10,11).

Crew members were asked to report problems they were encountering with non-compatible aircraft lighting. Crew members on all three types of aircraft reported that interior lighting consists of a mixture of compatible and non-compatible sources. Pilots and co-pilots reported problems with glare on the windscreen from reflected light from other crew positions (9,10,11). The C-130E pilots and co-pilots frequently commented that the radar altimeter was an non-compatible source which caused reflections and interfered with their ability to see both inside and outside the cockpit (9). Much of the exterior lighting of the aircraft is non-compatible with the NVGs, although crewmembers reported very little difficulty with this.

Some of the exterior lights are covered with infrared filters, and in operational environments the aircraft's exterior lighting is turned off (9,10,11).

In order to overcome some of the problems created by non-compatible cockpit lighting, crewmembers must often modify the aircraft before a NVG mission. Pre-flight taping of lights is often performed, and chemical lights are then used when light is necessary. Visual tasks must also be modified during a NVG mission. Most pilots and co-pilots reported that they must alter their scan patterns by moving their heads more due to the decreased field of view through NVGs. They also reported wearing the NVGs slightly higher to allow a larger field of view when looking under the NVGs to scan the instrument panel. Another frequent modification is the use of counterweights to balance the weight of NVGs upon the head. Rolls of pennies are often used for this purpose (9,10,11).

"Crewmembers were asked to indicate the frequency of twenty-five different visual effects or difficulties associated with the use of NVGs during ground operations, flight operations, or following NVG flight". Some of the common difficulties encountered included height misjudgment, clearance misjudgment, confusion with lights, limited field of view, and limited depth perception. Pilots reported limitations in depth perception and field of view most commonly. Crewmembers were also asked to rank the order in which certain improvements in NVG should be accomplished. Pilots ranked NVG resolution, field of view, and weight as things that need improvement in the near future.

Crewmembers would also like to see interior lighting with rheostats installed in aircraft so that the light level can be adjusted to the user's preference (9,10,11).

Terrain features which were most commonly cited as difficult to detect while wearing NVGs included gradually rising terrain, "shadowed" objects, mountain ridge lines, roads, low rolling hills, and water. Most crewmembers who had participated in Desert Shield/Storm felt that the terrain features there were extremely difficult to perceive, as the homogenous nature of the gradually sloping sand dunes made goggle flight quite a challenge (9,10,11).

When asked how the use of NVGs affects the performance of their visual tasks, the pilots as a group expressed very few problems in the performance of their tasks with NVGs. Pilots noted that the use of NVGs makes the detection of turn points and terrain features much easier (9,10,11). One co-pilot remarked, "without them we cannot operate" (9). The C-5B pilots noted that without NVGs, their mission of covert landings would be impossible (10). C-130E crew members cited formation flight and aerial refueling as examples of tasks which could not have been performed by them during Desert Shield/Storm night missions without the use of NVGs (9). Other crew members reported more NVG problems with fatigue, the need for refocusing, and the limited field of view. In general, most crewmembers felt that, "NVGs are an essential and excellent tool for the mission which they must accomplish" (9,10,11).

Although NVGs have revolutionized military aviation and warfare, there must be further development in NVG technology and training. It appears that very few U.S. Air Force pilots have been trained in the usage of current NVGs. Proper fitting, adjustment, and focusing procedures must be taught to NVG crewmembers. Studies have shown that without proper training, crewmembers are not able to optimally adjust and focus NVGs, and that improvement is gained when aircrew members participate in instruction on proper NVG adjustment procedures (8). The U.S. Air Force has made a step in the right direction in coming up with a standardized training program, but must now require that all personnel using NVGs have current NVG training.

Permanent NVG compatible lighting with rheostats should also be incorporated into all interior and exterior aircraft light sources. This would be in adherence with the military lighting specification discussed above which states that light must be visible without NVG but must not interfere with the use of NVG. This would eliminate the need to spend time and money converting aircraft lighting each time a NVG mission is to be flown.

The weight of NVG should be decreased as well. ANVIS is a significant improvement over the PVS-5 in terms of weight, but a further reduction must obviously take place since this issue was ranked so high by pilots and other crewmembers. However, this may be difficult to accomplish since improvement in visual field must occur as well, and increasing the field of view makes the NVG heavier and longer.

Lastly, resolving capability and field of view must be improved. With an increase in resolving capability should come increased depth perception as well. Again, the problem here is the inverse relationship between resolution and field of view. Technology seems to be the limiting factor. With technological gains should come NVGs capable of increased resolution, depth perception, and field of view. A new all-purpose NVG called the NOVA-8 is now being tested (1). This goggle reportedly has a sixty degree field of view (1).

Current night vision goggles do meet the needs of U.S. Air Force cargo pilots to a certain extent. Military aviation is becoming more "night friendly" through the use of devices such as NVGs. According to Marine Colonel Carl Fulford, "In Vietnam we never conquered the night. It belonged to the enemy" (4). Things are changing. Many of the night-time missions which were carried out in Desert Shield/Desert Storm may not have been possible without the use of NVGs. However, further research should be done to improve both the quantity and the quality of night-time vision for military aviators.

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