Analyzing The Interactions between Brown-out Accidents and Night Vision Equipment in Military Aviation Accidents:

Loss of a UK RAF Puma Helicopter on Operational Duty in Iraq, November 2007

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Abstract

Night vision devices mitigate the risks associated with operations in low levels of visibility. They help personnel to maximize visual resources through image intensification or infrared imaging. However, night vision devices also create new risks. They encourage personnel to conduct operations that would otherwise have been rejected. They also create a host of human factors problems that are implicated in a growing number of military accidents. In particular, the operation of night vision equipment has been associated with several different forms of spatial disorientation. The following pages describe how this disorientation exacerbates the hazards created by 'brown-out' landings that occur when visibility is reduced by airborne particles, typically from helicopter downwash. The opening sections of this paper provide a high-level review of night vision operations and of previous accidents related to 'brown out' incidents. Subsequent paragraphs focus on a more detailed case study leading to the loss of a Royal Air Force Puma on operational duty in Iraq during November 2007. The closing sections of this paper argue that there is an urgent need to go beyond Boards of Inquiry. We must extend the scope of operational studies across the US and UK armed forced to ensure that we learn the lessons provided by the loss of this Puma and the growing number of similar accidents, which stem from complex interactions between new technology and a range of environmental hazards, including but not limited to 'brown out' and 'white out' conditions.

1. Introduction

Many armed forces have begin to realize that accidents kill more military personnel than enemy action. In 2006, 95 members of the UK Armed Forces were killed in 'mishaps' (50% of all deaths). During the same period, 33 regular military personnel were killed in action and 14 died of wounds as a result of deployment in Iraq or Afghanistan (25% of all deaths) (DASA, 2009). The financial consequences of these adverse events are also important; armed forces stretch finite resources between many different conflicts. In the last three decades US Army Aviators have been involved in almost 400,000 accidents costing in excess of $4 billion, (unadjusted for inflation). These figures have prompted Donald Rumsfeldt and his successors to introduce safety initiatives across the US Department of Defense. Table 1 shows how these programmes have gradually helped to reduce the total number of Class A to C Army Aviation mishaps from 236 in 2006, to 201 in 2007 and 191 in 2008[1]. However, progress has not been as

[1] Class A mishaps cost $1,000,000 or more and/or destruction of an Army aircraft, missile or spacecraft and/or fatality or permanent total disability. Class B incidents involve damage costs of $200,000 or more, but less than $1,000,000 and/or permanent partial disability and/or three or more people are hospitalized as inpatients. Class C incidents are slightly more

rapid, or as uniform, as many would like. Expressed as an accident rate there were 7.583 Class A to C flight accidents per 100,000 hours in 2006. This had risen to 10.357 in 2007 but fell again to 7.639 in 2008 (Fabey, 2008).

Accidents remain relatively rare events for most armed forces. It can, therefore, be argued that short term reductions in the accident rate may reflect statistical variations linked to other factors rather than underlying changes in military safety management systems. Most accidents are caused by interactions between different causes and contributory factors. They stem from problems that lie undetected for months or years, including flaws in the design of equipment, Standard Operating Procedures (SOPs) or maintenance procedures. These longer term 'latent' issues combine with 'catalytic' events that trigger particular accidents, such as human error or component failures. They are often compounded by operational demands, including meteorological conditions, mission requirements and by enemy action. It is also important to remember that there is a residual risk in many combat and training activities that create the potential for accidents; where young people are typically asked to make critical decisions in short periods of time with limited information. These complexities do not arise in many civil environments and hence it can be particularly difficult to sustain reductions in the military accident rate (Johnson, 2007).

Total Aviation Accidents (Flight, Flight-Related, Ground & UAS)				
	Number of Accidents			
Accident Category	**FY 2008**	**FY 2007**	**FY 2006**	**3-Yr Avg**
Aviation Class A	26	34	27	29
Aviation Class B	31	32	61	41
Aviation Class C	134	135	148	139
Total Aviation (Class A-C)	191	201	236	209

Table 1: US Army Aviation Accidents (2006-2008)

There have been more than 120 US Army helicopter crashes in Iraq since 2001; just over 40 were caused by enemy action. In Afghanistan, there have been approximately 40 helicopter crashes, around one quarter were due to hostile fire. Many of these accidents have occurred while crews were using night vision equipment. For instance, the US Army recently found that there were 7.7 serious incidents per 100,000 hours of daylight flight in their helicopter fleet. The rate rose to 13.9 per 100,000 hours for night flight. Of those, the rate for unaided night operations was 9.3 while 15.8 incidents occurred per 100,000 hours for night operations involving vision enhancement systems (Johnson, 2004). There are many reasons for the higher incident rates associated with the use of night vision technology. For example, night operations carry an inherently greater risk than missions that are conducted during daylight hours. Image intensification and infrared systems tend to support operations that would not otherwise be attempted. There are also technological and human factors limitations; night vision devices do not turn night into day. The relatively constrained field of view afforded by many applications can lead to spatial disorientation. Macuda et al. (2004) have investigated the difficulties that aviators experience when using night vision systems to identify forms that are recognised by their motion. The studies of Macuda and their colleagues have shown that the relatively low image quality of many night vision systems can

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complex as the categorization changed in 1992. Prior to that date they were defined to incur damage costs of $10,000 or more, but less than $200,000 and/or non-fatal injury resulting in loss of time from work beyond day/shift when injury occurred and/or non-fatal illness/disability causes loss of time from work. After 1992 this was revised to be damage costs of $20,000 or more, but less than $200,000 and/or non-fatal injury resulting in loss of time from work beyond day/shift when injury occurred and/or non-fatal illness/disability causes loss of time from work.

impair aviator performance and increase workload. Existing applications provide relatively grainy images that can prevent users from identifying depth, motion, resolution, form, size and distance information.

The operational characteristics of existing rotary aircraft, such as the CH-47, has led to an increasing number of accidents in which debris from helicopter downwash has obscured crew vision during landing and takeoff (US Army Aviation, 2007). The decision to focus on the interaction between night vision and 'brown out' incidents is further justified by the operational demands that continue to face the NATO International Security Assistance Force (ISAF) in Afghanistan and coalition troops in Iraq. The operational context for these conflicts has created a requirement for formation flying to deliver troops and supplies into the field. The first aircraft to land or take –off in a formation stands a greater chance of avoiding the debris that affects their colleagues. However, in some areas even a single take-off can generate a dust cloud that extends for miles. A recent US Air Force report argued that the task of landing in desert environments was the "most dangerous aspect of flying in combat helicopters today" (US Air Force, 2008). Fixed wing vehicles also suffer from the problems of 'brown out', especially during sandstorms. However, the frequency of these incidents is much lower and the consequences are typically less serious than for helicopter operations. A US Air Force helicopter pilot with fast jet experience recently summarised the differences by arguing that "there is really no relaxation point with them. The pilot is constantly making adjustments to combat instabilities present during hovering. You compensate these instabilities by becoming a human Doppler - that is, you detect and react to states of position and motion. When visibility goes away so, too, does knowledge of the motion state. If a pilot can't detect motion state, then that pilot is likely seconds away from crashing" (US Air Force, 2007).

The hazards created by 'brown out' incidents are exacerbated by the restricted peripheral vision and low resolution that is provided by night vision systems. Debris on landing and take-off obscures visual references and increases the spatial disorientation that is a common cause of many accidents involving image intensification and infrared technologies. These problems are compounded by a sense of complacency that can arise when aircrews rely on the images provided by night vision technology. Many incident reports refer to the sense of surprise when pilots are first engulfed by the dust brought up in the wash of their own rotors (Dept of Army, 2001).

This section has introduced the importance of night vision technology and of brown out incidents in military accidents involving rotary winged aircraft, Section 2 goes on to provide a more detailed analysis of the operating characteristics of night vision devices. The third section uses the findings from this work to identify interactions between night vision devices and the environmental or meteorological conditions that lead to brown out incidents. The intention in the first half of the paper is identify the causes of previous incidents and consider the technological or operational limitations of recent proposals to reduce the frequency of brown-out accidents. In contrast, the second half of this paper looks at a single case study. In particular, Section 4 focuses on the loss of a UK Puma helicopter on operational duty in Iraq during November 2007 (RAF, 2007). This incident stemmed from environmental conditions that limited the effectiveness of night vision equipment. Contributory factors included organizational issues, such as a failure to follow Standard Operating Procedures, and a host of human factors concerns, including the problems of maintaining distributed situation awareness across multiple teams.

The aircraft involved in this incident formed part of a mixed formation of two Pumas and two Lynx helicopters. During the afternoon before the accident, a plan emerged to attack a series of targets under the cover of darkness. However, intelligence updates forced the Mission Leader to re-brief the formation on a revised scenario for the attacks. During the flight, the lead Lynx became separated from the rest of the formation and radio contact was lost. However, the Mission Leader believed he had correctly identified one of the targets and a landing area. During an initial approach, the second Puma struck the ground and rolled over under 'brown-out' conditions as debris was lifted into the air from the downwash of the rotors. The aircraft caught fire shortly after impact; two passengers were trapped in the wreckage and were later found to be dead by a subsequent rescue crew. The damaged Puma was destroyed in place by coalition forces. In order to understand the conditions that caused and exacerbated this accident, it is first necessary to analyze the strengths and weaknesses of the night vision devices that the crews were wearing. Subsequent sections consider the effects that brown out conditions can have upon the operation of these devices.

2. The Role of Night Vision Devices in Military Aviation Accidents

Night vision devices mitigate the risks associated with operations in low levels of visibility. They help personnel to maximize visual resources; however, night vision devices also create new risks. They create a host of human factors problems that are implicated in a growing number of military accident reports (Johnson, 2004). The use of night vision equipment can impair situation awareness (Durnford et al, 1995). It can also distract pilots from other information systems and hence increases the likelihood of an adverse event. However, it can also be argued that these devices tend to be used under adverse meteorological and environmental conditions when accidents are more likely to occur anyway. For instance, approximately half of all accidents involving the US Army's Black Hawk helicopter fleet have occurred while pilots were wearing night vision devices. However, this does not imply that these incidents were caused by the night vision devices. Many more accidents might have occurred if aircrews had not been wearing these devices.

Studies of aviation accidents have identified the spatial disorientation that can be caused by the use of night vision devices in helicopter operations (Braithwaite et al, 1998). Problems with depth perception and orientation were found to predispose aircrew to mishaps involving night-aided flight. Three independent assessors read through each of the incident reports in the A to C categories in order to identify those that involved some form of spatial disorientation. These were then subject to a further analysis that was intended to identify 'associated factors' and 'possible countermeasures'. They found that approximately 43% of all spatial disorientation mishaps occurred during flights that used night vision equipment. Only 13% of accidents that did not involve spatial disorientation involved these devices. An examination of the spatial disorientation accident rates per 100,000 flying hours revealed a significant difference between the rate for day flying and the rate for flight using night vision devices. The mean rate for daytime flight was 1.66, while the mean rate for flight with night vision devices was 9.00. They concluded that the use of night vision devices increased the risk of a spatial disorientation accident by almost five times.

2.1 Overview of Night Vision Technology

There are two main classes of night vision devices. Image intensification (I^2) systems enhance the lighting that is available within the existing environment. Infrared (IR) devices, in contrast, will typically use heat emissions to identify objects that cannot otherwise be detected using available light sources.

Image Intensification Equipment: Image intensification systems support direct observations by amplifying low levels of ambient light. Most image intensification systems perform poorly in total darkness. Higher amplification is associated with more expensive devices and can imply increased levels of distortion. The intensified image is, typically, viewed on a phosphor screen that creates a monochrome, video-like image, on the user's eyepieces. Unfortunately, a number of disadvantages affect the application of this technology. Most image intensification systems are attached to the users' helmet. Early models included relatively heavy battery packs that restricted the users' head movements. This problem was exacerbated by the need to move the head because many of these devices offer a highly restricted field of vision. This may only be 40-60 degrees (Canadian Army Centre for Lessons Learned, 2001). Image intensification equipment can also create problems in depth perception. Colour cues and binocular information are lost with many commercial systems. All of these limitations are being addressed by technological innovation. In particular, it is now possible to buy light weight and extended field of vision systems. However, these tend to be expensive and can be difficult to maintain under field conditions.

As mentioned, image intensification (I2) systems amplify available light. From this it follows that, I2 systems do not work well in near total darkness. External light sources support the use of this equipment. City lights provide useful illumination when cloud cover reflects available light back onto a scene. However, there is a risk that personnel will fixate on distant light sources (Johnson, 2004). Looking at the moon has the same effects as looking directly at the sun under daylight lighting conditions. Flares can also provide the indirect light that is amplified by image intensification systems. However, such a strong source will adversely affect device resolution if users look directly at them. Vehicle instrument lights and cockpit displays can create “washout” or halo effects. It is usually possible to turn-off instrument illumination in ground vehicles. However, it is a complex and expensive task to alter cockpit lighting systems without compromising the daytime use of the aircraft. Night vision systems are often particularly sensitive to the red lights that are frequently used in speedometers and engine instruments. The anti-collision lights required by FAA regulations can also be intensified to a point at which they dazzle the wearer of an intensification system.

Visual acuity from night vision devices provides a vast improvement over human night vision. However, it is far from perfect. As with direct sight, higher levels of acuity are associated with closer, slower targets (Macuda et al, 2004). The visual acuity offered by image intensification rapidly diminishes for objects over 500 feet away. This distance is further reduced, the faster the target is moving. A number of environmental factors can also reduce the acuity of image intensification systems. In addition to brown outs, performance is also affected by rain, clouds, mist, dust, smoke and fog. All of these factors imply that experience and recurrent training must be provided if personnel are to operate image intensification systems. Risk assessments should also consider the problems that can arise, for example if external lights are likely to create the deep shadows that hide hazards or if the users of image intensification systems are momentarily dazzled by other light sources.

Infrared and Thermal Imaging Systems: Rather than enhance light that is visible to the human eye, thermal imaging systems detect infrared radiation that is emitted by heat sources. These devices use transducers to detect thermal emissions that can then be focussed in the same way as conventional light. The difference in temperature amongst the objects in a scene is translated into a visual contrast represented by different shades on a display. Infrared systems can, therefore, be used in total darkness. They tend to be robust against the light ‘pollution’ that will dazzle users of image intensification systems. Infrared devices can also be used to ‘see through’ some types of fog because they do not rely on visible light.

The sensitivity of thermal imaging systems is measured in terms of degrees celcius per optical *f*-number. In other words, it provides an indication of the temperature change that would be required to provoke a change in the image. These differences are typically in the region of 0.05-0.2 degrees Celsius. The resolution or sharpness is measured in terms of the instantaneous field of view (IFOV) in milliradians (mrad). 17.5 milliradians is equal to an angle of 1 degree in the instantaneous field of view. The lower the IFOV value is then the sharper the image and the longer the range will be. However, as the magnification of the thermal sensor increases, the field of view decreases. Operators must use scanning techniques to compensate for this limitation. Without well developed methods, it can be easy for users to overlook areas in a scene. As with image intensification systems, individuals can quickly become fatigued by the prolonged scanning that is required to use infrared systems in combat conditions (New Zealand Army, 2003)**.**

Infrared landing lights are invisible to the naked eye but for can provide useful beacons to aircrews using these night vision systems. Infrared searchlights can be used to pick out objects that could not otherwise be detected using visible light. However, these sources can help enemy personnel if they are also using night vision equipment. There are further human factors limitations. Users tend to limit their attention to the area directly covered by a searchlight. They must be trained to expand their scanning patterns on either side of the beam. There are further limitations. High-humidity reduces the thermal contrast that is amplified by infrared systems. Rain and surface water on runways can create optical illusions; they often appear to be further away as the surfaces cool. Infrared systems cannot be used to identify precise details on remote objects that are not distinguishable by different heat profiles. Brown-out can also occur when there are reflections from an infrared searchlight caused by the dust that is raised in a rotor wash.

2.2 Training with Night Vision Devices

Previous paragraphs have summarized the operating characteristics of existing night vision systems. These operating characteristics make it important that individuals and teams are trained in the operational use of these applications. It can be difficult to master the scanning skills that are required to avoid the 'washout' and 'halo' effects that occur when image intensification systems are affected by secondary light sources. Similarly, personnel must be trained to overcome the limited field of view provided by most infrared applications (US Army Center for Army Lessons Learned, 2003). US Army Training Circular 1-210 'Aircrew Training Program Commander's Guide to Individual and Crew Standardization' summarizes training and familiarization requirements for the use of night vision equipment (US Department of the Army, 1996). Prior to their first training flight with night vision, aviators must spend more than an hour in the cockpit of a static simulator or aircraft to familiarize themselves with a list of basic tasks including emergency procedures, night vision failure and a 'blind' cockpit drill. They must then undergo ten hours further training including:

- An Introduction to Night Vision Devices;
- Night terrain interpretation;
- Night Vision ground and air safety;
- Night tactical operations, including the impact of lighting;
- Night Vision navigation, including map preparation;
- Aircraft modification requirements for night vision flight;
- Vision, depth perception, and night vision orientation.

TC 1-210 also includes requirements for aircrews to conduct refresher training in the use of night vision devices. One hour of refresher training is required if a night vision flight has not been completed on a particular aircraft type within the previous 180 consecutive days. There is also a requirement for aviators to conduct mission training. This involves at least ten more hours of flight using night vision devices followed by a further evaluation.

While it is possible to train personnel during particular flight conditions, it can be far more difficult to prepare operators to resist the broad range of visual illusions that complicate the operation of night vision technologies. For instance, many devices can provide an impression of a false horizon on the boundary between light and dark colored areas of sand, especially when other environmental factors, including dust and haze, obscure the true horizon. Desert conditions often also lack the visual markers and reference points that support accurate height perception. Under such circumstances, ground lights can be mistaken for the lights of other aircraft or even stars. Lack of features and relatively slow speeds may also persuade pilots that they have stopped moving even though the aircraft is actually travelling forward. In flat terrain, such as that found in dry lakebeds, infrared devices create the illusion that terrain slopes upwards at the edges. Particular problems are created when using the infrared searchlights to view other helicopters that may appear to be landing into a crater when they are landing on level ground.

Recent years have seen a move away from training individual crewmembers to recognize the optical illusions that affect night vision equipment. These illusions can be so persuasive that individuals will still fall prey to them even though they have been trained to recognize that they can occur. In contrast, greater attention has recently been paid to team and crew coordination as a potential barrier to incidents and accidents. For instance, the US Army Safety Center’s Southwest Asia Leaders' Safety Guide emphasizes the need to synchronize crew observations and communications in order to combat some of the problems created by these illusions. Guidance is provided on scanning responsibilities for pilots and non-rated crewmembers in different types of flight. These responsibilities must be planned and rehearsed prior to any mission so that team members can detect and compensate for the current limitations of night vision technology. Team selection, therefore, becomes particularly important. This issue will be referred to several times as a contributory factor in the case study that is presented in Section 4.

3. Brown-out, Rotor Wash and Military Aviation Accidents

Training requirements, such as those presented in TC1-210, have improved competency to a point where most military mishaps are the result of several different causal factors. Operational demands often combine with environmental conditions to exacerbate the problems of using complex technologies; including night vision equipment (US Army Centre for Lessons Learned, 2003a). As we have seen, the operation of night vision equipment has been associated with several different forms of spatial disorientation. These effects are exacerbated during a ‘brown-out’ landing or take-off when visibility is reduced by airborne particles. These particles are, typically, raised from helicopter downwash in the last 20 to 30 feet of an approach. The interaction between night vision equipment and brown-out incidents is important because it typifies a growing number of ‘complex’ or ‘systemic’ military accidents.

Brown-out accidents were relatively rare during the Cold War; given the small number of operations in arid desert regions. However, the importance of these mishaps has steadily increased even though brown-out accidents tend to be more ‘survivable’ than other aviation incidents. They, typically, occur close to the ground and at low airspeed. The UK MoD has lost 16 helicopters in brown-out incidents between 2000 and 2007. Between 2002 and 2005, the US Army suffered 41 brown-out accidents. Approximately, 80 percent were during landings and 20 percent during takeoffs (US Army Aviation, 2007). The percentage of these accidents as a proportion of all Class A mishaps rose from 9% prior to the invasion of Iraq to 18% during it (Jennings, 2008). Since 1991, the US Army has reported more than 230 cases of aircraft damage and/or injury due to unsuccessful take-offs or landings in brown-out conditions. One reason for the importance of brown-out incidents is that they lead to spatial disorientation which exposes other underlying vulnerabilities. These include human factors issues. Inadequate training, problems in cockpit resource management, high levels of workload combine and undermine attempts to cope with the loss of visibility during an approach (Johnson, 2007a). Brown-outs also expose flaws in the design and maintenance of airframes. For instance, mechanical failures have been triggered by the ingestion of sand. Brown-outs accelerate wear on rotor blades and gear as well as engine components and air filters. Secondary effects include the reduction of maintenance intervals and the consequent increase in demands on support crews. High levels of maintenance workload continue to be a significant cause of other military accidents.

3.1 Effects of Brown-out on Different Platforms

New generations of aircraft, such as the HH-60G PaveHawk and the MH-53 PaveLow, have been specifically developed to support extreme low-level operations. However, the threats created by 'brown-out' conditions are beginning to constrain the 'all-terrain' landing capability that these platforms were intended to provide. This is particularly important because the amount of debris generated in brown-out incidents is also determined by the downwash characteristics of the airframe or airframes involved in an approach. For instance, the performance characteristics of the V-22 Osprey make it particularly susceptible to these incidents. This aircraft relies on tilting rotors that increase the velocity of the downwash compared to other rotary winged aircraft such as the CH-46, which it was intended to replace. However, the precise relationship between rotor aerodynamics and downwash incidents is far from simple. For instance, the Osprey seems to be less prone to low altitude brown-out. In other words, the debris clears in the last few feet before the tilt-rotor makes a landing. Further study is required to develop a comprehensive account of the downwash characteristics of different aircraft. The Osprey observations are largely based on accounts from aircrew transitioning between the V-22 and the CH-46. Accident data provides more quantitative insights. For example, the CH-47 made 7% of all U.S. Army helicopter flight hours from February 2003 to June 2005. However, it was involved in 30% of all brown-out mishaps, 12 out of 41 in total between FY 2002 and 2005 (POGO, 2007, US Army, 2007).

Downwash directly influences the likelihood of brown-out mishaps. A number of other design factors influence the consequences of these incidents. For example, the AH-46D Apache has a relatively narrow stance; the pilot sits in a rear section of the cockpit while the co-pilot/gunner sits immediately in front. This tandem layout makes the aircraft more susceptible to 'roll-over' incidents in a brown-out compared to the parallel cockpit layout and broader stance of UH-60s. However, the Apache also provides a Forward Looking Infra Red vision system that is being integrated with image enhancement systems as part of the Arrowhead upgrades. This arguably helps the aircrews to avoid the disorientation associated with brown-out incidents. UH-60s only provide image intensification technology.

3.2 Training, Tactical and Procedural Countermeasures

As with night vision related accidents, many military organisations have developed Training, Tactics and Procedures (TTPs) to reduce the likelihood of brown-out mishaps. One reason for this is that the US Army has identified 'spikes' in the accident rates. Brown-out incidents are more likely to occur in the early stages of combat deployment (Gant, 2007). Aircrews must rely on unprepared field sites prepared – for example in forward arming and refuelling laagers, combat outposts etc. Over time these sites are upgraded with hard-standing areas using gravel, concrete and polymer coverings that are less prone to brown-out. However, aircrews cannot assume that they will be able to land on a prepared area. There is, therefore, a continuing requirement to ensure they are proficient in the monitoring skills that are essential to maintain situation awareness during brown-out conditions.

Arguably one of the most effective Training, Tactics and Procedures is to keep the debris behind the pilot's door by performing a rolling landing. This helps to ensure that the crew have a clear view of the Landing Zone (LZ) ahead of them. Rolling approaches are less effective if the wind changes during a landing or if the prevailing wind prevents such an approach in the first place. There are further limitations. For example, ground obstacles and wires often restrict the area available within a landing zone. Other aircraft may require additional space to make their own approach. They can also create debris ahead of the potential LZ; obscuring the view of the rest of the formation. There may not be time for a prolonged rolling approach in medical evacuations (MEDEVAC), unscheduled supply drops or rapid troop transports. These techniques cannot be used in situations where enemy action may target the aircraft as it moves forward through the dust cloud. These factors constrain the airspeed and rate of descent needed to maintain aircraft control under brown-out conditions (US Army Center for Combat

Readiness, 2005). More acute descent and ascent profiles have been developed to minimise the impact of brown-out. However, these manoeuvres create their own risks by placing heavy demands on the skill and proficiency of aircrews.

The US Army has also developed their TTP support to ensure that instructors from units that are being rotating out of a combat area are then heavily involved in training their colleagues from new rotations. This was not always the case. One of the reasons why brown-out incidents have been so prominent in recent military accidents is because there has been a mismatch between pre-deployment training and operations experience. Early US rotations in Iraq were more accustomed to the dry lakebeds and scrub of the National Training Centre. This left aircrews unprepared for brown-outs and a host of other operational conditions. They had relatively little experience of shifting sand dunes and the impact that extreme temperatures can have upon night vision equipment. For instance, crews found that their training manuals authorized airspeeds that were too fast to safely operate at night over sand dunes with night vision equipment; "the authorized airspeed for nap of the earth flight is 40 knots, but an aircraft flying in zero illumination at 25 feet in sand dunes should fly just ahead of effective transitional lift…Just keep in mind that at airspeeds below Effective Translational Lift (ETL), you may encounter rotor induced blowing sand" (US Army Safety Center, 2003b).

Other TTP countermeasures focus on crew resource management. There is a temptation to 'stack the deck' with additional pairs of eyes during landing – for instance by requesting input from the door gunner in another platoon. However, there is a risk that misunderstandings and other forms of communication failure will compromise shared situation awareness. The use of TTP solutions is further limited by one of the fundamental paradoxes of military risk assessment (Johnson, 2007). In order to become proficient in the communication and planning techniques that reduce the threats created by brown-out incidents, it is necessary for crews to practice these skills. However, it can be difficult to train in brown-out conditions when Standard Operating Procedures (SOPs) are intended to limit aircrew exposure to these hazards. In the decade between the Gulf War and Operation Enduring Freedom, the U.S. Army recorded over 40 cases of brown-out accidents during training.

Some units in the US Army have begun to remove the cabin doors to increase visibility for the aircrew during brown-out landings. Pilots and co-pilots can make more accurate direct visual observations by maximizing their field of view so that they can spot any 'breaks' in the clouds of dust and other debris. As with the application of polymer binding agents, this solution has not been adopted across all units. In particular, the US Air Force TTPs have not approved the removal of cabin doors because there remain considerable concerns about the consequent loss of protection in combat areas.

3.3 Ground-Based Countermeasures

In addition to specialised 'brown-out' approach profiles, US Army SOPs require that aircrews use prepared landing zones (LZ) whenever possible. These are mostly confined to established bases and outposts. Prepared LZs are seldom available in forward operating areas or for deliberate air assaults. Aircrews must improvise landings on dirt roads, open dry areas, or dusty mountain peaks (U.S. Army Combat Readiness Center, 2005). The hazards associated with landing on unprepared surfaces are exacerbated by the difficulty of conducting detailed landing site surveys in hostile areas or where operational demands force late changes to the location of a mission. In other words, crews often do not know whether or not they will face brown-out conditions when they are tasked with a particular mission.

A range of materials have been developed to reduce the amount of debris that can be raised during take-off and landing. The US Army have laid down polyester Mobi-Mats, or 'triscuit pads', since the late 1990s. These are temporary pads that can be unrolled to provide a stable surface for rotary wing operations. However, they are heavy and can be unwieldy in the field. In consequence, the US Marine Corps have experimented with light-weight HeliMat alternatives (Whittle, 2007). These do not have the load bearing characteristics of the Mobi-Mats. They also wear out under a high tempo of operations. Operational deployment has, therefore, revealed the need to carry both type of synthetic surface.

'Rhino snot' polymers provide a further alternative to these pre-formed surfaces and mats. These substances bind together debris prior to any landing. In order to apply these polymers, ground forces must first scrape off as much dust as possible. The area is then soaked with water, leveled and topped with gravel. Several coats of 'Rhino snot' are then applied and left to harden. Eventually, the surface breaks up to minimize longer-term environmental effects. However, the polymers offer a different set of logistic problems to those created by HeliMats and MobiMats. In order to bind surface layers, the polymers are very adhesive. This makes them difficult to handle. If clothes are contaminated then they, typically, must be destroyed. This makes the polymers very unpopular with some of the units that have to apply them. The difficulty of cleaning the equipment used to lay down the surfaces often forces ground units to reserve a small number of vehicles for this purpose. This also means that the approach cannot easily be used in forward areas.

3.4 Airborne Countermeasures

The operational risks associated with brown-out landings and take-offs have motivated initiatives to find technological countermeasures. The most obvious approach is to redesign rotors that reduce the likelihood of a brown-out occurring in the first place. The US 101 variant of the Augusta-Westland EH101 has been designed with blades that are intended to push debris away from the fuselage. Traditional designs tend to propel dust towards and around the cockpit area. However, brown-out performance is one of several competing requirements for blade design and here can be trade-offs with efficiency/power, noise etc. Aerodynamic solutions to the hazards created by brown-out remain the subject of basic research (US Air Force, 2007).

It is unlikely that aerodynamic innovations in rotor design will provide a panacea for brown-out incidents in the short term. Flight information systems provide an alternative approach. For example, some MH-53's present a cross in the middle of the head-up display at 15 knots of descent. As the pilot decelerates this cross descends towards a reference box and hence can be used to monitor vertical velocity (Martin, 2008). The Brown-out Situational Awareness Upgrade (BSAU) extends this approach. Vertical speed and vector information is mapped using data from radar altimeters and the Global Positioning Systems (GPS) on aircraft including the UH-60 and CH-47. Aircrews can access BSAU information using their standard head-up displays as well as through their night vision goggles. The design teams first identified information needed by aircrews to mitigate the risks of brown-out accidents. They then traced this required information back to the available input from sensor data. These sensors had to be sufficiently accurate to ensure that the application did not increase the cognitive load on aircrews when they used the symbology during a brown-out. However, US Army studies concluded that BSAU was only an initial step; "While the system proved its value during this and many other approaches, good crew coordination, briefing of go-around procedures, and power management remained critical tasks" (US Army Center for Combat Readiness, 2004).

Flight symbology systems, such as BSAU, help pilots to monitor their attitude and rate of descent into brown-out landings. They cannot at present be used to help aircrews avoid terrain features or ground obstacles. Night vision equipment can provide pilots with additional cues. They may also reduce the impact of disorientation. However, these devices often limit aircrews' field of view and hence may exacerbate rather than reduce the problems of spatial awareness. The underlying technologies are also susceptible to brown-out failures. Dust particles can completely obscure the narrow field of view provided by image intensification equipment, such as that installed on most Blackhawk aircraft.

Airborne debris reduces the temperature profiles that are augmented in infrared systems. Further problems arise from the interaction between night vision equipment and the hazards created by brown-out incidents. For example, the FLIR (Forward Looking Infra-Red) pod and infrared countermeasure equipment have been slung beneath the HH-60G. The location of these devices makes them particularly vulnerable; "even the most experienced pilots are not immune from breaking FLIRs or rolling an aircraft due to a brown-out approach" (US Air Force, 2008).

A number of research programmes are developing enhanced night vision systems to address the problems created by brown-out landings. These include 'see and remember' applications that take a series of FLIR images of a landing zone before they are obscured by debris from the downwash. Software then recreates a pseudo-3D image for the aircrew to refer to during a subsequent brown-out. The Photographic Landing Augmentation System for Helicopters (PhLASH) has extended this 'see and remember' approach to image intensification systems. PhLASH combines an electro-optical sensor and infrared strobe lights to match a photograph of the ground with a coordinate on the Earth's surface using onboard GPS. The intention is that the photograph would be taken immediately before the brown-out and hence could be ten or twenty seconds out of date during the final stages of the descent. This could create problems is vehicles or other elements of a formation moved into the LZ. It can also be difficult to obtain an accurate image of the LZ during night operations, given the limitations of image intensification and infrared technologies that were summarized in the opening sections of this paper (Martin, 2008). This limitation can be addressed through the use of radio wave sampling (US Air Force, 2008). The Defense Advanced Research Projects Agency (DARPA) Sandblaster programme provides an example of one of these 'next generation' initiatives. This integrates four different technologies:

1. *A radar sensor for three-dimensional scanning.* Conventional radar plots provide two dimensional overviews of a potential LZ. Phased and millimeter wave approaches can be used to build up three dimensional representations while the radar signals penetrate the debris that causes brown-out incidents.
2. *A database to store successive scans of a potential landing zone.* The results can also be compared to pre-stored images and maps. This helps to ensure that whenever possible the radar returns can be mapped onto a known potion of the landing zone.
3. *Synthetic vision techniques to generate a representation of the LZ for the crew based on sensor feedback and the pre-stored information in the database.* The intention is that this view will restore aircrew situation awareness that would otherwise be compromised by a dust cloud.
4. *An 'agile' flight control system.* The ambitious aim of this component is to enable the helicopter to 'land itself' under low speed approaches (Martin, 2008).

Much work remains to be done before sufficient operational expertise has been gained to demonstrate the reliability of this multi-stage approach – for instance in desert environments where sandstorms continue to alter the landscapes that may be recorded in spatial databases. US Air Force work in this area has focused on Laser Detection and Ranging (LADAR). In contrast to millimeter wave radar based on radio pulses, LADAR uses light sources to scan a potential landing zone. This technology has been applied in 'near operational conditions'. However, there are further technological problems. Ideally, aircrews require high resolution images (e.g., 1280 x 1080 pixels). However, existing LADAR sensors have low spatial resolution (i.e., 512 by 512 pixels). Real-time systems also suffer from the same limited field of view, around 30 to 60 degrees, that affects night vision systems. Accuracy requirements for brown-out countermeasures can be expressed in terms of centimeters at rages of 100 to 1000 ft in real time. At present the generation of synthetic images requires additional processing that prevents these resolutions being produced in real time. These limitations are being addressed by technologies that include active gated LADAR imaging and fusion of the millimeter wave radar from other areas of the Sandblaster programme. A recent Department of Defence research call also proposed the integration of LADAR technology with image intensification and infrared night vision equipment (US Department of Defense, 2008).

The US Army Safety Centre has stressed that these technological initiatives will not remove the need for to train crews to combat brown-out conditions. There is a need to familiarize pilots with the strengths and weaknesses of advanced sensing systems, just as aircrews must gain expertise in the application of infrared and image intensification equipment. The UH-60M and the CH-47G have recently been deployed to US forces and provide technological support for brown-out landings. While they do not provide the integrated sensing systems mention above, they do provide velocity vector, acceleration cursor, instantaneous vertical speed indicators, radar altimeter, and heading information on a common 'hover page'. Pilots are not forced to piece together critical information from numerous displays scattered across the cockpit. However, the Safety Center recognizes that the wider provision of this technology will require "the development of a separate aircrew training manual (ATM) task for landing without visual reference for all airframes, not just special operations aircraft" (Gant, 2007).

4. Combating the Interactions between Night Vision and Brown-outs

Training, Tactics and Procedures (TTPs) have been developed to minimise the disorientation that can be cause by night vision equipment. Previous sections have also described how TTPs have been drafted to address the loss of spatial awareness during brown-out landings. There are strong overlaps between these Training, Tactics and Procedures s. For example, the UH-60 requirements include a section on "Night or NVG Considerations":

> "A go-around should also be initiated if visual contact with the landing area is lost. Snow, Sand and Dust Considerations: If during the approach, visual reference with the landing area or obstacles is lost, initiate a go-around or instrument takeoff (ITO) as required, immediately. Be prepared to transition to instruments. Once visual meteorological conditions are regained, continue with the go-around" (Gant, 2007).

Training is required because it is recognized that there is a position close to the ground where it may be more risky to attempt a go-around rather than complete the landing. Hence, go-arounds should be initiated well before passing below any obstacles. However, brown-outs can occur in the last few feet of a descent. In other words, the aircrew must decide whether or not to abort the landing after they have passed underneath obstacles and at a time when it can be difficult to determine whether the go-around is more risky than the landing. All of these factors are exacerbated when aircrews are under fire or operating in close support of ground troops with an urgent operational need for air support. The use of night vision equipment adds further complexity because it can foster a sense of over-confidence in crews as they approach a potential landing site. This may leave them ill-prepared for the disorientation caused by an unexpected brown-out. In such circumstances, the US Army guidance makes it clear that the greatest risks arise when crews have no contingency plan and so must continue with a landing even though they are uncertain of their precise orientation with respect to the intended LZ. Aircrews must train to continuously scan for any available outside cues and for information from their instrumentation during brown-out contingencies.

Simulators cannot easily be used to prepare for the spatial disorientation that occurs when brown-outs create sudden on-set instrument meteorological conditions (IMC), especially while using night vision equipment. "Simulation is a valuable tool to aid in training aviators in the dust landing profile, and it is getting better all the time, but it cannot replace the feel, motion and characteristics of the real thing" (Gant, 2007). Equally, there are significant hazards in practicing under the environmental conditions for which aircrews are not yet fully prepared. In consequence, a range of visors, helmet bags and 'foggles' have been developed to restrict the vision of aircrews during exercises (Rash, 2006). These help pilots to experience some of the effects of brown-outs under controlled supervision in normal visibility. In particular, a great deal of attention has recently focused on the integration of Night Vision Goggle Power Interrupt Devices (NVGPID) into US military TTPs. NVGPIDs help crews simulate the loss of NVG capability during brown-outs (Gant, 2007). Instructors can use the devices to induce a failure in the night vision goggles during a critical phase of a practice landing. By extension, the same technique can also be used to replicate the impact of debris during take-off. The intention is to force the pilot to make use of the instruments and symbology to complete the maneuver. There are three additional benefits. Firstly, the NVGPID device is relatively cheap and simple. Secondly, instructors do not always have to fail the night vision system during practice landings; this makes it possible to mimic some of the uncertainty that arises when crews do not know whether or not a brown-out will occur. Finally, instructors can control the level of risk that is implicit within any brown-out drill outside the constraints of a simulator. Training officers can vary the stage of an approach or landing when a failure is induced. They can also integrate the NVGPID into other operational training scenarios to mimic specific approach patterns. It is far more difficult to preprogram complex simulation software to reflect the specific demands of a deployment. It is important to stress, however, that the use of NVGPID's is intended not simply to replicate the loss of spatial cues. These devices have been developed to help crews simulate the large volume of communication, coordination, and visual, instrument and symbology scanning that is required following a brown-out.

5. Case Study: Loss of a UK Puma in Iraq, November 2007

The opening sections of this paper summarized the strengths and weaknesses of night vision technology for military rotorcraft operations. Image intensification and infrared devices provide significant spatial cues during low-visibility landings. They can help crews to survey potential landing sites and to develop contingency plans before a brown-out occurs. However, night vision devices contribute to the disorientation that leads to brown-out accidents. Poor resolution and a limited field of view are exacerbated by the loss of external cues as debris and dust are raised by rotor downwash. The previous analysis has been based on accident studies, on TTPs and on statistical evidence drawn from several military organizations. In contrast, the second half of this paper uses the insights provided from the high-level review to consider the specific causes and contributory factors that led to a brown-out accident involving a UK Royal Air Force Puma on operation in Iraq during November 2007. The loss of night vision, combined with the disorienting effects of dust and debris, exposed underlying problems in aircrew communication, in training and in mission planning.

This incident occurred during a night mission that involved a mixed formation of two Pumas and two Lynx aircraft. For convenience we distinguish between Puma 1, carrying the mission leader, and Puma 2 that was lost in the accident. During the afternoon before the mishap, a plan emerged to attack a series of targets under the cover of darkness. However, intelligence updates forced the Mission Leader to re-brief the formation on a revised attack scenario. During the flight to the target area, the lead Lynx became separated from the rest of the formation and radio contact was lost. However, the Mission Leader believed he had correctly identified one of the targets and had located a potential landing zone. During an initial approach, Puma 2 struck the ground and rolled over under 'brown-out' conditions as debris was lifted into the air from the rotor downwash. The aircraft caught fire shortly after impact; two passengers were trapped in the wreckage and were later found to be dead by a rescue crew. The damaged Puma 2 was destroyed in place by coalition forces.

5.1 Qualification for the Mission

Previous sections have described how armed forces have used training as a means of reducing the risks associated with the use of night vision equipment under brown-out conditions. The subsequent investigation examined the qualifications for the pilot handling the Puma at the time of the crash and found “It was not possible to ascertain his Night Vision Device (NVD) category, as it was not obvious in either his Log Book or his training records. It was clear that he had flown to NVD Cat B limits but there was no reference to any Cat B conversion course having taken place. Therefore although not theoretically qualified as NVD Cat B he had proven himself competent to fly to Cat B limits and the lack of a dedicated training course, although remiss, did not play a significant part in his handling of the events leading up to the crash” (Royal Air Force, 2007). The training documents for the Non-Handling Person (NHP) in Puma 2 also “indicated that he had not completed the full NVD Cat B work up but he was sufficiently trained and experienced to be expected to carry out the NHP duties as required by his aircraft commander” (Royal Air Force, 2007). The crewman onboard Puma 2 had completed his Full Mission Qualification workup to a ‘high standard’ but there was no record in his training folder that the qualification had been awarded. “Neither is there a record in his training folder of his award of NVD Cat B qualification”. The Non-Handling Person on Puma 1 was ‘suitably experienced and capable’ to undertake his role on the operation. However, he too had not completed his NVD CAT B training. His night tactical formation qualification had also expired.

The Board of Inquiry argued that ‘in-theatre’ experience made up for the lack of NVD Cat B training. This argument is supported by relatively high frequency of brown-out incidents during the initial stages of any deployment and subsequent rotations (U.S. Air Force, 2009). Aircrews seem to be less likely to be involved in brown-out accidents the longer that they have been deployed in environments where they are likely to encounter these conditions. However, the crews involved in this accident did not all have the same level of experience in these environments. The handling pilot of Puma 2 was approaching the end of his first detachment as a Full Mission Qualified aircraft commander. However, he had considerable previous experience as a Non Handling Person with a total of 1,700 flying hours and around 830 in the Puma. The Non-Handling Person (NHP) in Puma 2 had around 430 flying hours on the Puma. However, he had only recently been deployed to Iraq and had limited opportunities to familiarize himself with the rest of his crew. Similarly, the pilot, non-handling person and crewman on Puma 1 had only been together for six weeks at the time of the accident. These findings are particularly significant given the emphasis that many military organizations are placing on mutual situation awareness and inter-crew communication during brown-out conditions (US Army Centre for Lessons Learned, 2003a). RAF doctrine and course descriptions covering the operation of night vision devices also stress the need to provide aircrew not just with practical experience using image intensification and infrared devices but also with a theoretical understanding of the underlying technologies. Brown-out incidents have shown that past experience in a combat area may be insufficient to prepare crews for the particular demands that are created when their approach options are tightly constrained, for example, by enemy fire on an unprepared landing zone.

The crews of Lynx 1 and 2 lacked experience of working with Pumas. There had been no pre-deployment training between Lynx and Puma aircraft nor was there any ‘in-theatre mixed-type workup package’. The Puma force argued that the risks of in-theatre training were too great and that the operational tempo left little time for such exercises. This argument is supported by the observation, made in previous sections, that the US Army had more than 40 brown-out accidents during training between the Gulf War and Operation Enduring Freedom. However, more recent US doctrine maximizes training opportunities to support crew resource management both within and between aircrews in the same formation. For the Puma and Lynx crews, the absence of mixed formation exercises and the relative lack of familiarity between recently formed teams undermined their ability to practice the communications that are vital to maintain mutual situation awareness. The MOD has taken steps to address many of these issues; for instance by conducting closer audits over the training records of RAF pilots. They have also increased the amount of practice Joint Helicopter Command aircrews receive in the ‘desert box’ rolling landing techniques, described in previous sections, for example as part of

Exercise Jebel Sahara. However, this accident clearly reveals continuing areas of concern in terms of aircrew training and preparation for the interaction between brown-out incidents and the use of night vision devices.

<u>5.2 Mission Planning</u>

The initial mission briefing provided generic information about the weather, light levels, intelligence, air tasking orders etc. It also provided an opportunity for the crews to conduct detailed formation planning for night operations, including the development of contingency plans for brown-out landings. The fact that this planning did not take place should not be over-emphasized. Those plans that were developed had to be considerably revised as intelligence updates forced major changes in the mission. A further problem was that several key members of the aircrews were missing during the briefings. The accident took place on the same day as a change in the engineering rotation. In consequence, servicing had to take place earlier than might otherwise have been expected, at the start of the aircrews' duty period. Some crewmembers had to support the engineering teams at the same time as others were taking part in mission briefs. These absences together with the uncertainty over the NVD status of crewmembers may be symptomatic of an ad hoc approach, which although it may be understandable given the operational tempo, reveals underlying concerns in the planning and staffing of missions.

The final mission planning was conducted by the Non Handling Person of Puma 1. He was too busy planning to attend some of the mission briefings and arguably could have been better supported by members of the other crews. However, as noted previously, some were still helping to service their aircraft. The investigators concluded that although the plans were well made; 'there was much confusion as to the exact nature of the target sets and the number of landing sites that were to be visited, suggesting that there was a great deal of confusion amongst all parties'. The final air mission brief summarized all of the potential target sets and described the final roles for all of the aircraft in the formation. Two additional Pumas, 3 and 4, were to be held as a Quick Reaction Force.

A new mission target was identified while the crews were moving to their aircraft. This urgent new operational requirement seems to have obscured the fact that the crews had not received an adequate briefing. This may in turn be explained by the lax way in which final mission authorization was interpreted to permit such ad hoc changes late in the planning process. In consequence, the Mission Leader briefed the rest of the formation over the radio. This new tasking required a far more demanding sortie profile that the mission that had previously been planned and briefed. The aircrews may have under-estimated the risks associated with 'in flight' briefings without detailed contingency plans, even given the need to respond to a time-limited target opportunity.

It was dusk when the formation departed their 'home' landing site but light levels were high. A number of obstructions were spotted during the flight. These included wires that forced them to fly higher than he crews would have preferred. The Non-Handling Person on Puma 2 reported high levels of workload. Chatter on the Air Traffic and tactical radios interfered with his task of updating successive grid references generated as the target moved position. The formation closed in, a couple of miles before the last known target reference.

<u>5.3 Closing on the Target</u>

With around one mile to go before Puma 2 reached the target, it became clear that Lynx 1 had overshot to the South by around a mile due to an error in their navigational equipment. The over-flight alerted elements of the target forces to the potential attack. In the meantime, Puma 1 and Lynx 2 failed to establish radio contact with the missing crew. The remaining formation could now see that the correct target indication was now some three miles behind them to the North. The Mission Leader requested infrared ground illumination on a known location to help navigate back to proposed landing area. They then instructed Puma 2 and Lynx 2 to join Puma 1 on a direct route to the target. This left Lynx 1 detached from the formation. The Team leader of ground forces was also on the Mission Leader's Puma 1 and together they conducted a rapid briefing on a revised approach to the target. However, the aircraft were now deployed in an unfamiliar formation without a full briefing and only the most rudimentary of contingency plans. Some of the aircrews were newly formed and all lacked training in mixed formation operations. Although the crews had experience in the operational of night vision devices, their theoretical training in the limitations of those devices may also have been lacking. This illustrates the argument in earlier sections that brown-out incidents exacerbate or expose underlying weaknesses in the command and management of military operations.

The crew of the remaining Lynx 2 struggled to identify the target using their night vision capability during the final stages of their approach. They, therefore, decided to conduct an early overshoot. Meanwhile, the Mission Leader had not registered the latest intelligence updates on the location of the target and so urgently sought further clarification. He assumed that the target was now located to the South. He, therefore, altered course at relatively low levels; these were often below the Radar Altimeter warning which, as mentioned previously, had not been reset below the transit settings. Lynx 2 now rejoined the other two Pumas having recovered from the overshoot. He remained at a safe distance to assess what they were doing. The Handling Pilot of Puma 2 was also unsure about the intentions of the Mission Leader as the target could still not be seen. The crew of Puma 2 now believed that Puma 1 was making a final approach as their speed was further reduced. Puma 1 then performed an abrupt right turn and radioed the other units that they were under fire. This was the first time that any of the units had made visual contact with the targets. Puma 1 then began approaching a field adjacent to the target area in a manner that made it clear to the crew of Puma 2 that they were about to land. The Handling Pilot of Puma 2 elected to follow the Mission Leader and land in the same field, which appeared to be flat and stable enough to support a landing.

5.4 Approach to Landing

It is usual practice for Handling Pilots to announce to others in the formation that they are committed to a landing when the performance characteristics of their aircraft no longer allow for the maneuver to be aborted. However, Puma 2 made the 'committed' call during a very early stage of the approach. This made it difficult for the crew to judge the eventual problems created by the constraints on the landing zone and the brown-out conditions. Their decision to make this early call was justified by their desire to support Puma 1 as it came under enemy fire.

The dust cloud raised by the down wash of Puma 1 demonstrated that ground debris would impair visibility on landing for Puma 2. However, this did not prompt the crew of Puma 2 to revise their radar altimeter settings to provide additional assurance on their descent. The late turn by Puma 1 also left Puma 2 with very limited space to land – this ruled out the rolling 'box' approach techniques that have been advocated in US and British military doctrine. In consequence, Puma 2 performed an almost vertical descent from 75 feet. The degree of difficulty was further exacerbated by a surface wind of 5-10 knots. The handling pilot was so focused on the demands of landing the aircraft that he did not notice when one of the troops began firing on the targets from the right door of his Puma. The crewman and the non-handling pilot stated that this did distract them from their tasks.

From about 30feet, a significant dust cloud gathered around the descending Puma. Ground references became harder and harder to maintain. The handling pilot stated that he was able to maintain visual references throughout the descent. However, 'they were of varying quality and mainly consisted of moving dust and straw'. He did not arrest the initial descent in time and hit the ground. The resultant 'heavy landing' did not exceed the 3G limit that would have triggered the Helicopter Emergency Egress Lighting System nor did there appear to be any structural damage. The collective was not lowered and the Puma maintained around 10 degrees of pitch. Partly in consequence, the aircraft continued its forward motion. It also began a rolling oscillation that increased as the aircraft slowed. The handling pilot was concerned that the Puma would roll over. He decided to overshoot the landing without clear visual references. The handling pilot reiterated that he chose a level attitude for takeoff but did not verify this using his instrumentation. He raised the collective and felt the Puma start to climb. The low main rotor RPM audio warning sounded twice; possibly as a result of the handling pilots quickly raising the collective.

At this point, the Non-Handling Person saw a Lynx at 10 o'clock. He informed the pilot but considered that there was no chance of a collision given their relative positions. The pilot also recalls seeing the Lynx through the brown-out and became increasingly concerned that there was a danger of collision. The non-handling person stated that he did not think this was likely. However, the pilot decided to halt the climb and carry out a level transition into horizontal flight. The intention was to gain airspeed and move the aircraft away from the dust cloud. He did not check his instruments nor did he establish a visual horizon (RAF, 2007). As he began this maneuver, they reentered the dust cloud and lost all visual references. The Board of Inquiry argued that this disoriented the crew to such an extent that they lost an accurate sense of the effects that their commands were having on the aircraft. As the pilot began to level the wings he felt an accelerated roll to the right with the noise and control motions that might be associated with the blades striking the ground. The aircraft continued moving to the right while more dust began to block out all external visual references. The crew could, however, feel the blades striking the ground until the aircraft finally came to rest some five seconds after the initial impact. Both of the aircrew had their night vision devices dislodged during the 'landing'. Fortunately, the emergency lighting system was activated to assist the egress from the damaged aircraft. As mentioned in the introduction, the aircraft caught fire shortly after impact. Two passengers were trapped in the wreckage and were later found to be dead by a subsequent rescue crew. The damaged Puma was destroyed in place by coalition forces.

6. Contributory and Causal Factors behind the Puma Case Study

The subsequent Board of Inquiry considered a wide range of causal and contributory factors. For example, they discounted aircraft technical failure and aircraft performance. They also excluded 'other hazards'; there were no reports of loose wires or bird activity. Enemy action, sabotage and friendly fire were discounted. The rounds fired towards Puma 1 do not seem to have hit Puma 2. The investigation also concluded that the lack of integration between the Lynx and Puma Standard Operating Procedures (SOPs) was not a major influence on the incident. Similarly, it was argued that the 'cockpit gradient', which prevents junior colleagues from questioning the actions of their senior team members, was not a contributory factor. The following section summarizes those contributory factors that were identified by the Board of Inquiry. This analysis provides a clear illustration of the range and diversity of underlying operational and command problems that are exacerbated by brown-out incidents using night vision.

6.1 Meteorology

Meteorological conditions contributed to this accident. The crew of Puma 2 experienced significant downwind during their approach. This led to a loss of lift and a higher than anticipated rate of decent earlier than would otherwise have been expected. The initial heavy landing was, therefore, the consequence of an uncorrected increase in the rate of descent caused by this downwind component. Meteorological conditions also had a direct impact on the brown-out. As the crew approached the landing zone, they might have expected the dust cloud to form behind them given their descent profile. However, the downwind component created brown-out conditions below the aircraft at a much earlier point in the landing than might have been anticipated. The wind also blew debris ahead of the aircraft making it much harder for the crew to judge their rate of descent and attitude. Finally, the investigation argued that the downwind component exacerbated the Puma's tendency to over-rotate forward during transition and led to a nose down attitude that increased the rate of descent.

6.2 Light Levels and Night Vision Device Performance.

The Board concluded that 'The Op training directive states that all crews should be both NVD Cat B and Night Tactical Formation qualified prior to Basic Mission Qualification (BMQ) training. The Handling Pilot, Non-handling Person of Puma 2 and Non-Handling Person of Puma 1 were not correctly qualified to NVD Cat B before their BMQ training. A review of qualifications is underway". However, the subsequent inquiry argued that the performance of night vision equipment and ambient light levels were not contributory factors in this accident (RAF, 2007). The sun set approximately one hour before the crash and the crews reported that ambient light levels were workable. The sun's afterglow was visible in the second Puma's 9 or 10 o'clock position but it was not mentioned as a distraction in testimonies after the accident. It is noticeable that the Board of Inquiry did not consider the operational strengths and weaknesses of the night vision devices that were available to the crews. This is beyond their remit. In contrast, separate hearings in Coroner's courts increasingly criticize the UK MoD for failing to adequately consider the operational performance of the equipment that they provide (BBC 2007, 2008, 2009). Coroner's hearings give families of the injured and bereaved valuable opportunities to voice their concerns over military procurement. However, their criticisms often lack the detailed engineering and technical input that is required to develop constructive proposals and avoid future failures. There is an urgent need to develop procedures by which the findings of Board of Inquiry can be extended to maximize the lessons learned from previous accidents in a manner that is both technically convincing and which elicits the support of all stakeholders, including both surviving personnel and the relatives of any casualties. This is all the more important when many defense suppliers only take a passing interest in the ways in which their equipment actually performs under operational conditions (Johnson, 2007). Most of the companies involved in the development of night vision equipment have no processes for gathering 'lessons learned' from incidents such as the loss of the Puma.

6.3 The Dust Cloud.

The Board of Inquiry treated the dust cloud as a distinct issue from the light levels and the performance of night vision equipment. It was argued that light levels did not contribute to the accident, even though the crew was wearing NVG's for which they did not have the full CAT B training. However, the approach was conducted into a 'significant' dust cloud that robbed the handling pilot of visual references; "Despite the crew's utilization of the latest UK NVD technology they ended up being close to the ground but unable to see the surface due to dust". This sentence illustrates how the Board viewed night vision technology as part of the solution to brown-out and low visibility landings rather than a potential exacerbating factor in spatial disorientation. In contrast we have sought to draw links between the spatial disorientation that has been identified as a key problem both in the use of night vision equipment and in brown-out landings.

6.4 Disorientation

The loss of the Puma stemmed in part from the disorientation of the crew. The Handling Pilot initially reported that he lost visual references at around 15 feet on final approach. However, he subsequently contradicted this statement. It is clear, however, that he experienced some difficulty in judging his rate of descent and after the first impact was 'flying blind' within the debris that was raised by the rotor wash. He could not, therefore, judge the extent of the subsequent roll and this contributed to his decision to overshoot. His attention was focused on external cues rather than monitoring his instrumentation. This made it difficult for him to obtain adequate visual references so that he could judge the rate of climb. The crew was able to glimpse the Lynx but this was also in motion. Any references would be relative to the trajectory of that aircraft and could be very misleading. The crew, therefore, lacked the necessary information to identify the effects of any attempts to transition forward. Arguably, they could not determine whether they were ascending, descending or turning.

6.5 Terrain

The landing area was relatively flat, however, it was crossed by a rectangular grid of irrigation ditches around 2 feet deep and smaller furrows of around one foot in height. It was very dusty. There was a significant risk that an aircraft might strike one of these ditches. The subsequent investigation argued that "if a thorough recce of the field had been carried out, these features would have been noticed and an appropriate landing would have been chosen to avoid any run on, making oscillations (following a ground strike) unlikely" (RAF, 2007). Of course, any decision to reduce the run-on would have correspondingly increased the likelihood and consequences of a brown-out by further constraining the use of the rolling box approaches that have been described in the opening sections of this paper. This argument again stresses the need to look in more detail at the complex interactions that arise under military operations; where a change in tactics might reduce exposure to one potential risk while at the same time increasing the likelihood of other hazards. By trying to avoid the terrain hazards through a vertical descent, the aircrews would increase the dangers of a brown out landing.

6.6 Approach Profile

The landing area was seen by the crew very late in the approach of Puma 2. There was also pressure to land when they observed the tracer close to Puma 1. The handling pilot may, therefore, have felt very constrained in terms of the potential areas in which he could complete a landing. This led him to follow a non-standard vertical approach profile that was 'inappropriate in dusty conditions as height judgment is very difficult and references are very difficult to maintain" (RAF, 2007). In consequence, the handling pilot lost the cues necessary to arrest the descent.

6.7 Supervision

The fact that Puma 2's handling pilot had not passed an appropriate Cat B NVD training course was included within this supervisory analysis. The Board argued that this might have reflected a potential problem in crew selection procedures. However, as mentioned, they did not consider the consequences of this lack of training in their analysis of light levels, weather and the impact of the dust cloud. One possible consequence of this decision to assess NVD competency within crew selection was that the Board rejected the handling pilots NVD training as a contributory factor 'in itself'. Similarly, the non-handling person's lack of training was also considered narrowly in terms of the insights it provided into the supervision of crew composition rather than the 'systems issues' in terms of the interaction between terrain, meteorology, NVD operation and approach trajectory. The observation that the non-handling person's logbook indicated NVD CAT B competency when he had not completed the desert environment qualification was, therefore, dismissed as a contributory factor by the Board. Instead they argued that the Handling Pilot's concern to reduce the inexperienced Non-Handling Person's workload, by taking over the tactical radio net etc, may have contributed to the accident. Similarly, the Non-Handling Person in Puma 1 was found to be 'incorrectly qualified' for the mission having an out of date 'Night Tactical Formation' qualification and not possessing the NVD Cat B qualification. Again, these omissions were not found to be contributory factors except that they added to the sense that the crews were working at, or beyond, their operational capacity; "the fact that all 4 crewmembers were working very hard meant that no one took stock of the situation and no one was balancing the risks that were taken". **If the lack of NVD qualifications had been identified as a contributory factor in this accident then many crews would have been grounded until they completed the courses that would become prerequisites for subsequent missions. This would have created heavy burdens on those crews that did posses CAT**

B qualifications at a time of rising operational demands. We must consider whether the risks of deploying personnel without CAT B NVD training outweigh the operational benefits of tasking them to use this technology on missions that have significant tactical importance for ground forces? This question extends well beyond the Puma case study. The development of innovative technologies, including multi-sensor fusion for the visualization of brown-out approaches, increases rather than reduces the need for appropriate training. In the future, leaders will still have to determine whether their troops have sufficient training and expertise to use these systems in complex combat missions.

6.8 Operational Pressure

It is hard to underestimate the importance of operational pressure as a factor in the decision to task this mission to the Puma and Lynx crews. There was an urgent need to get the mission underway and this eroded the time that would otherwise have been available for mission planning. Changing intelligence also forced late revisions to the plans. There is a suspicion that had the mission been successful, leaders would have been commended for improvisation. In the circumstances, however, it is clear that a re-brief might have helped crews consider likely contingencies during the approach to the landing sites. The inquiry argued that after the loss of the lead Lynx, the formation did not know the disposition of the target and hence 'operational pressure both real and perceived was a contributory factor'.

6.9 Authorization Process

The authorization of missions provides a process of checks and balances that are intended to safeguard military personnel. However, the formal mission approval process must also provide leaders with sufficient flexibility to respond to changing intelligence; environmental factors; resource constraints etc. The standard format in place at the time of this accident was deliberately designed so that approval did not need to be written out in full for every sortie. Instead, pro forma authorization sheets were used. In this sortie, they were signed at such an early point that the authorizing officer could not discuss the limits or nature of the task. It was, therefore, difficult for the authorized captain to explain those critical mission constraints to the rest of the crews. Many military organizations now have an expectation that leaders will explicitly request briefings or 'resets' when they are unsure of essential mission parameters (Johnson, 2008). In contrast, the authorization sheets asked the crews to do any tasking that they were asked to do without caveat or recourse to the chain of command. The authorization process had evolved under operational pressures to the point where "it removed the final check of understanding and confirmation of crew suitability for the task at hand" (RAF, 2007).

6.10 Briefing Process

The failure of the authorization process to establish mission parameters and guide crew composition was compounded by the operational pressures. Together these factors constrained the briefing process that is intended to act as a foundation for mission safety. The briefings described missions that were never flown; changing intelligence forced successive revisions to the plans. Even so, senior personnel were missing from the briefings in order to complete other tasks, including aircraft servicing. This removed an opportunity to provide guidance to the less experienced crew members and, theoretically, alter the deployment and composition of the teams. Quick Battle Orders (QBOs) were used to brief the crews in-flight. These may have been ambiguous – for instance over whether Puma 1 or the remaining Lynx was the mission lead. The QBOs were not passed on to the reserve Puma's 3 and 4. This is a significant omission given that the Deputy Leader was in Puma 3. The reserve Pumas also carried more experienced crews who might then have realized the complexity and risks of what was being proposed.

6.11 Formation and Deployment

The task of communicating Quick Battle Orders was complicated by radio problems within the formation. This was said to be a common occurrence – something that itself is a priority 'lesson' from this accident. After the mission it was unclear whether messages were not received, or whether they were missed by crews dealing with high workload or by they were using other radios or that had the volume turned down. Such uncertainty again underlines the need for a more systematic review of communications within these formations. As noted previously, Lynx 1 missed the target area and divided the formation. This created uncertainty for Puma 2's handling pilot about the position of the missing Lynx as he attempted the overshoot. It also created potential confusion amongst all elements by undermining the formation and mission brief. Crews could no longer rely on de-confliction plans between the Lynx and Pumas. The eventual deployment was based on Quick Battle Orders using an untried combination of one Lynx and two Pumas. The nature of the QBO's, the communications problems and the failure to brief all crews on intelligence updates about the location of the target added to the risks associated with this formation. The Board summarized these findings by arguing that 'there was a significant breakdown in Crew Resource Management across the formation with a low standard of leadership and 'followership' being displayed throughout" (RAF, 2007).

6.12 Adherence to Standard Operation Procedures (SOPs)

After the mishap it was argued that the crew of the Puma had accepted a role that was not described within the existing SOPs. This contributed to the lack of clarity in mission objectives and tactics that was observed in previous paragraphs. In particular, the emerging plan did not identify an Initial Point (IP). In formation flying, these act as a rendezvous and help to ensure that aircrews approach a target along an agreed route from a known location. Initial Points also help to coordinate a series of final checks, including making adjustments to the radar altimeter warnings. These warnings are initial set en route to a target to a level that ensures they are not triggered every time the aircraft crosses raised ground. However, they are then reset for the descent into a landing zone. The crew of Puma 2 never agreed on the IP and hence they flew a beyond the transit phase without having set the Rad Alt to 25ft for the final approach contrary to the SOP for Puma dust operations. After the accident, it was found that the Handling Pilot directed the Rad Alt audio warning should not be reset for approaches as a matter of course. This decision was not questioned by the rest of the crew and the same policy also seems to have been adopted by others in the squadron. The subsequent board noted that 'this was not the view of the 22 Sqn training staff who believed it should be set at 25 feet for all dust approaches, without exception' (RAF, 2007). This contradiction between official SOPs and everyday operations illustrates the complexity of military accidents. The decision not to reset the Rad Alt warning contributed to this accident. However, the crews' actions were also motivated by a desire to reduce intrusive and distracting warnings. There are further human factors concerns when spurious alarms significantly increase the workload on crews on approach to a landing site.

Local practices diverged from SOPs in a number of other ways. For example, Minimum Safe Heights were not commonly calculated for this area of operations. The accident also found examples where there were no SOPs to support crew operations. In particular, the individual Standard Operation Procedures for Puma and for Lynx aircraft did not describe what should be done during joint operations. This created considerable mutual uncertainty; neither knew the procedures associated with their colleague's platform.

Table 2 summarizes the contributory factors that were identified or excluded from the official Board of Inquiry into the loss of the Puma. The scope of this table illustrates a point made in the opening sections of this paper – military accidents are 'systems failures'. They stem from complex interactions between many different issues. The diverse nature of the issues presented in this table also illustrates the way in which the additional demands created by operating night vision systems in brown-out conditions can expose a host of underlying problems in military operations ranging from the documentation of training and expertise through to briefing and approval processes and the development of common SOPs form mixed formations.

	Summary	Detailed comments
Cause	CFIT	The cause of the accident was controlled flight into terrain (CFIT) brought about by the handling pilot's disorientation due to the use if an incorrect technique for a dust take-off.
Excluded	Aircraft technical failure	
	Aircraft performance	
	Light levels.	
	Other hazards	Not caused by loose objects, bird strike, incoming rounds.
	Supervision: Crew Composition	Puma 2 handling pilot had not completed Cat B NVD course.
	Supervision: Crew Composition	Puma 2 non-handling person had not completed Cat B NVD course.
	Supervision: Crew Composition	Puma 1 non-handling person incorrectly qualified.
	Enemy Action, Sabotage or Friendly Fire	
	Cockpit Gradient	
Contributory Factors	Weather	Unanticipated downwind component on final approach.
	Dust cloud	Inability to see usable references through dust.
	Terrain	Lack of detailed reconnaissance.
	Supervision: Command & Control	Air Advisor & Tactical Controller inexperienced in helicopter ops.
	Supervision: Crew Composition	Puma 2 handling pilot felt he had to reduce the non-handling persons workload and thereby increased the demands on himself.
	Supervision: Crew Composition	Inexperience in both the crews of Puma 1 and Puma 2.
	Supervision: Operational Pressure	Eroded planning time and left crews ill-informed on mission parameters.
	Supervision: Authorization	Conducted with such broad parameters that it removed a last chance to establish crew suitability for the task at hand.
	Briefing Process	Lack of full brief with all formation elements present.
	Formation and Deployment	Decision to split the formation undermined pre-briefed deconfliction points and attack plans.
	Approach Profile	Choice of vertical approach into a very dusty field.
	Non-Adherence to SOPs	Failure to follow SOPs for dust operations and especially to reset the Rad Alt to 25 feet.
	Disorientation	Puma 2 Handling Pilot was disoriented

Table 2: Summary of Contributory Factors Leading to the Loss of the Puma

7. Conclusions and Further Work

The contingencies and characteristics of asymmetric warfare increase the need to use night vision equipment while at the same time raising aircrew exposure to brown-out conditions. The pace of operations in Iraq and Afghanistan has increased the need for helicopter support in areas well beyond the reach of prepared landing zones. Changes in insurgent technology, including the use of remotely detonated IEDs, also encourage deployment under the cover of darkness (Johnson, 2009). Many military organizations were unprepared for the demands created by these conditions. In consequence, most have seen a rise in the frequency of brown-out-related mishaps. This, in turn, has motivated technological innovations, ranging from rotor aerodynamics through to binding polymers, from LADAR applications to sensor fusion techniques. However, these are active areas of research and much remains to be done before they can be deployed to support combat operations.

The opening sections of this paper have also described how Training, Tactics and Procedures (TTPs) have been used to tackle the threat of brown-outs in night vision missions. For instance, 'rolling box' approaches have been developed to provide the forward trajectory necessary to move beyond an initial dust cloud. However, there may not always be the space available to prepare such descents given the obstacles that litter many operational areas. Other constraints stem from the need to coordinate landings with ground forces and with other aircraft. Therefore, simulators and drills have been used to help prepare crews for the spatial disorientation and the loss of situation awareness that can arise during these incidents. For example, the US Army has introduced the Night Vision Goggle Power Interrupt Device (NVGPID) into their aviator training programs. Instructors can use these devices to induce the failure of night vision equipment to simulate debris from rotor-wash during take-off and landing. The intention behind the NVGPID program is to help ensure aircrews "train to continuously scan, and to train the ability to rapidly adjust from outside cues to instruments" (Gant, 2007).

The opening sections of this paper provided an overview of the interaction between night vision and brown-out accidents. In contrast, the second-half presented a more detailed analysis of the particular ways in which the disorientation associated with night vision equipment and brown-out operations can combine to expose underlying weaknesses in military operations. The focus has been on the complex causes and contributory factors that combined during the loss of a Puma on operational duty in Iraq. This mishap was triggered by the crews' loss of situation awareness. However, the immediate events leading to the accident stemmed from a wider range of latent issues. These included operational pressures, distractions as the aircraft came under ground fire as well as the loss of spatial awareness during a brown-out while the crew was wearing night vision equipment.

The official Board of Inquiry into the loss of the Puma revealed a number of issues that, although they were not identified as contributory factors, do form a stark contrast with the doctrine and practices in other military organizations. It was not possible for the investigation to use the existing logs and training records to determine the Night Vision Device category of the handling pilot of the aircraft involved in the crash. He had flown in operations requiring NVD Cat B conditions but there was no reference to any conversion course intended to bring him up to this level. Similarly, the Non-Handling crewmember of the Puma had not completed the full NVD Cat B training. Nor was there any record in his training folder that he had completed his Full Mission Qualification. It is difficult to argue with the Board's conclusion that the lack of NVD training was either a cause or contributory factor. They insisted that the operational performance of the crew demonstrated that they could perform to NVD Cat B levels. However, it seems clear from the initiatives in other military organizations that more could be done to train crews for the demands created by brown-out conditions. These initiatives will never be effective unless better records are kept of the training that aircrews have received and that these records must be used to inform mission tasking. Unless these issues are addressed then there is little point in investing in TTPs for brown-out conditions in NVG operations.

The causes of many of the incidents described in this paper can be traced back to the operational tempo in Iraq and Afghanistan. Incomplete training and partial records are symptomatic of the common pressures on UK and US forces to take on significant operational demands with finite resources. Ultimately, these pressures are a greater threat than those associated either with night vision operations or with brown-out conditions.

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References

BBC. Hercules Safety ‘Still Lacking’, 2007.
Available on http://news.bbc.co.uk/1/hi/uk/6406203.stm, last accessed February 2009.

BBC. MoD Criticised over Soldier’s Death, 2008.
Available on http://news.bbc.co.uk/1/hi/england/tyne/7318813.stm, last accessed February 2009.

BBC. Mother Questions Soldier’s Armour, 2009.
Available on http://news.bbc.co.uk/1/hi/england/leicestershire/7884270.stm, last accessed February 2009.

M.G. Braithwaite, P.K. Douglass, S.J. Durnford and G. Lucas, The Hazard of Spatial Disorientation During Helicopter Flight using Night Vision Devices. Journal of Aviation and Space Environmental Medicine, (69)11:103844, 1998.

Canadian Army Centre for Lessons Learned, Night Vision in Kosovo, The Bulletin, (8)1:6-11, April 2001.

Defence Analytical Services and Advice for National Statistics, Annual Summaries, UK Ministry of Defence, London, http://www.dasa.mod.uk/natstats/natstatsindex.html. Last accessed February 2009.

US Department of the Army, Aircrew Training Program Commander's Guide To Individual And Crew Standardization, Department of the Army, Washington, DC, 1996, Training Circular No. 1-210, Especially Chapter 4: Night Vision Goggles, Available on http://www.usarmyaviation.com/pubs/TC%201-210/START%20HERE.htm. Last accessed February 2009.

US Department of the Army, Aeromedical Training for Flight Personnel, Headquarters, Department of the Army, Washington, DC, 29 September 2000, Field Manual 2-04-301 (1-301)

S.J. Durnford, J.S. Crowley, N.R. Rosado, J. Harper and S. Deroche, Spatial Disorientation: A Survey of U.S. Army Helicopter Accidents 1987- 1992. Army Aeromedical Research Laboratory Technical Report, Report number AS-A298147, Fort Rucker, AL, 1995.

M. Fabey, US Army Aviation Accidents Prove Costly, Aviation Week's DTI, Aerospace Daily & Defense Report, 18th June 2008. http://www.military.com/features/0,15240,170045,00.html. Last accessed February 2009.

R. Gant, Night Vision Goggle Power Interrupt Device (NVGPID): A Simple Device to Train Crucial Skills, US Army Aviation, 22-26, April/May 2007.
Available from http://www.quad-a.org/Archives/07_Magazine/070405/GantApril-May07.pdf, last accessed February 2009.

G. Jennings, Down in the Dirt: Helicopter Brown-outs, Jane's Defence: Air Forces, 13th February 2008. http://www.janes.com/news/defence/air/jdw/jdw080213_1_n.shtml. Last accessed February 2009.

C.W. Johnson, Failure in Safety-Critical Systems: A Handbook of Accident and Incident Reporting, University of Glasgow Press, Glasgow, Scotland, October 2003. ISBN 0-85261-784-4.

C.W. Johnson, The Role of Night Vision Equipment in Military Incidents and Accidents. In C.W. Johnson and P. Palanque (eds.), Human Error, Safety and Systems Development, Kluwer Academic Press, Boston, USA, 1-16, 2004.

C.W. Johnson, The Paradoxes of Military Risk Assessment. In A.G. Boyer and N.J. Gauthier (eds.) Proceedings of the 25th International Systems Safety Conference, Baltimore, USA, International Systems Safety Society, Unionville, VA, USA, 859-869, 0-9721385-7-9, 2007.

C.W. Johnson, The Systemic Effects of Fatigue on Military Operations. In Proceedings of the 2nd IET Systems Safety Conference, The IET, Savoy Place, London, UK, ISBN 978-0-86341-863-1, 1-6, 2007a.

C.W. Johnson, Military Risk Assessment in Counter Insurgency Operations: A Case Study in the Retrieval of a UAV Nr Sangin, Helmand Province, Afghanistan, 11th June 2006. In P. Casely and C.W. Johnson (eds.) Third IET Systems Safety Conference, NEC, Birmingham, UK, 2008, IET Conference Publications, Savoy Place, London, 2008.

C.W. Johnson and L. Nilsen-Nygaard, A Systemic Approach to Counter the Threat to Public Safety from Improvised Explosive Devices (IEDs), Proceedings of the 27th International Conference on Systems Safety, Huntsville, Alabama, USA 2009, International Systems Safety Society, Unionville, VA, USA, Submitted, 2009.

T. Macuda, R. Allison, P. Thomas, G. Craig and S. Jennings, Detection Of Motion-Defined Form Under Simulated Night Vision Conditions. Society of Photo-Optical Instrumentation Engineers (SPIE) Proceedings, 5442-36, 2004.

C. Martin, In The Thick of It All: Surviving the Brown-out, Canadian Air Force, Flight Safety: Debriefing Newsletter, June 2008. http://www.airforce.forces.gc.ca/dfs/publications/debriefing/2008/6-eng.asp. Last accessed February 2009.

New Zealand Army, Lessons Learned from Initial Deployment of the Light Armored Vehicle (LAVIII), LAV Update Number 3, August 2003.

Project on Government Oversight, Brown-out Accidents Plague CSAR-X: Controversy Surrounds Air Force Selection. June 21, 2007. http://www.pogo.org/pogo-files/alerts/national-security/ns-070621-csar-x.html. Last accessed February 2009.

C.E. Rash, Flying Blind, Aviation Safety World, Flight Safety Foundation, 44-46, December 2006. Available on: http://www.flightsafety.org/asw/dec06/asw_dec06_p44-46.pdf, last accessed February 2009.

Royal Air Force, Board of Inquiry into an Accident Involving Puma HC1ZA938 on 20 November 2007 while on Operation in Iraq, UK Ministry of Defence, London, UK, http://www.mod.uk/NR/rdonlyres/7B287D03-5FB1-4F5C-951C-7E1E87C0F44A/0/boipuma_za938.pdf. Last accessed February 2009.

US Air Force, National Helicopter Experts Gather to Discuss Aerodynamic Solutions for Brown-out, Wright Patterson Air Force Base, USA, 2007. http://www.wpafb.af.mil/news/story.asp?id=123058808, Last accessed February 2009.

U.S. Air Force, J. Sherer, Brown-out, 2nd November 2008. US Air Force Safety Center. http://www.afsc.af.mil/news/story.asp?id=123085802, Last accessed February 2009.

U.S. Army Aviation, Owning the Aviation Edge: NVGPID: A Simple Device to Train Crucial Skills. p22. 2007-04. http://www.quad-a.org/Archives/070405/GantApril-May07.pdf . Last accessed February 2009.

U.S. Army Combat Readiness Center, BSAU: Improving Aircrew Situational Awareness During Brown-out, Flightfax, October 2004, (32)10, October 2004. https://safety.army.mil/Portals/multimedia/docs/magazines/flightfax/2004_issues/ffoct04.pdf, Last accessed February 2009.

U.S. Army Combat Readiness Center, Brown-out on the Battlefield, FlightFax, May 2005, https://safety.army.mil/Portals/multimedia/docs/magazines/flightfax/2005_issues/ffmay05.pdf. Last accessed February 2009.

US Army Centre for Lessons Learned, NVG Currency, A Perishable Skill —Currency is Not Proficiency, Flight Fax, (31)2, February 2003.

US Army Centre for Lessons Learned, Night Vision Goggles Desert Operations Lessons Learned - 13 Years in the Making, Flight Fax, Vol. 31, Number 4, April 2003a.

US Army, Army Aircraft Mishaps/Accidents and Percentage of Chinook Accidents, cited in Aerospace Daily & Defense Report, March 7, Volume 221, Issue 44, 2007.

US Department of Defense, Improve LASER RADAR (LADAR) Image and Data System Processing with Multi-Sensor Fusion in Vertical Lift Visual Degraded Environments, Navy Solicitation SBIR 2008.2 - Topic N08-147, Washington DC, USA. http://www.navysbir.com/n08_2/N082-147.htm. Last accessed February 2009.

B. Van Elsber, Anatomy of a Tragedy. Knowledge, Volume 3, February 2009, US Army Combat Readines/Safety Center, https://safety.army.mil/Knowledge_Online/Portals/february2009/Knowledge_February_2009.pdf. Last accessed February 2009.

R. Whittle, Combat Operations: Matting Down Brown-out, Engine Wear. Rotor and Wing Magazine, Wednesday, 1st August 2007
http://www.aviationtoday.com/rw/military/attack/14521.html, last accessed February 2007.