Degraded Modes and the 'Culture of Coping' in Military Operations: An Analysis of a Fatal Incident On-Board HMS Tireless on 20/21 March 2007

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Abstract

In many military operations, weapons safety is compromised by 'degraded modes of operation'. These are situations in which personnel must find 'work arounds' for the many different routine failures that complicate military life. In most cases, these ad hoc adaptations do not threaten safety. However, if these failures are not addressed they can gradually erode the barriers and other defensive measures that prevent casualties from occurring. This paper analyses a recent accident that led to the deaths of two members of the UK Royal Navy on-board a submarine that was participating in under-ice training and tactical evaluations with the US military. We show that degraded modes of operation not only contributed to the cause of this accident but also complicated the response to the emergency. The key insight from this study is to reduce the tolerance to routine operational failures in many military operations so that personnel are more likely to rectify problems rather than resort to 'work arounds' that jeopardize safety.

Introduction

Many safety-critical subsystems have a mean time to failure that it less than the intended operational life of the applications that they support. In such circumstances, designers and operators must work together to ensure that maintenance intervals are scheduled so that critical components are repaired or replaced before they fail. However, the shorter the maintenance intervals then the higher the costs will be. There is an incentive to delay intervention as late as possible without jeopardizing safety. Once a sub-system has failed, the same financial pressures can persuade managers to find 'work arounds' or ad hoc patches that enable operations to continue. In other words, operators learn to maintain system functionality under 'degraded modes of operation' (Ref. 1, 2, 3).

In military systems, these pressures are considerably more complex. For example, operational constraints can prevent personnel from replacing failed components that must be delivered along extended supply chains. This is a particular problem in naval operations in remote regions where it may not be possible to source replacement parts for weeks or months at a time. The pressure to maintain functionality in the face of sub-system failures can also be exacerbated by operational requirements in the field. The risk of working without any ground to air missile systems might, therefore, justify the continued operation of an application even though there may be well-known faults with that platform (Ref. 4). Partly in consequence, many military organizations rely on training and doctrine to help personnel find ways of working around design flaws that were not adequately addressed during the procurement of complex systems (Ref. 5).

Summary of the Case Study: This paper uses a recent case study to illustrate the impact of degraded modes on military operations. In particular, it focuses on a fatal incident involving Her Majesty's Ship (HMS) Tireless while the submarine was on deployment (Ref. 6). Two members of the crew were killed and others were injured[1]. The incident occurred while Tireless was taking part in an under-ice training and tactical evaluation exercise close to the US Applied Physics Laboratory Ice Station in the North of Alaska. At the time of the accident, the submarine was following Standard operating Procedures (SOPs) using Self Contained Oxygen Generators (SCOGs) to maintain the oxygen level in the vessel. SCOGs contain a mix of sodium chlorate and iron powder or of potassium and lithium chlorate. When ignited, the mixture smolders at about 600 °C to produce sodium chloride, iron oxide and oxygen. Given the temperatures involved, SCOGs must be insulated to maintain the reaction temperature and to protect surrounding equipment. Tireless was using these devices because the primary oxygen supply relied on low pressure electrolysers that were liable to trip if ice formed in the hydrogen discharge piping. The two crewmembers who were killed in the incident had been qualified to operate these SCOGs having conducted maintenance procedures on many

[1] The number of injured and the nature of their injuries was redacted from the published findings of the Board of Enquiry for reasons of confidentiality and security.

occasions. They were responsible for training other members of the crew on their operation. At 19:56, approximately an hour before the watch was due to change, these was a loud bang heard throughout the submarine (Ref. 6). The forward end of the vessel filled with smoke. This triggered both a fire alarm. The flood alarm was also raised because the explosion was sufficient to depress the manual flood alarm button in the Forward Escape Compartment (FEC). From this point on it took 44 minutes for personnel to regain entry to the FEC where the two victims had been working. The hatch doors leading from the forward bunk space to the FEC were blown shut causing them to buckle and to jam in place. Several small fires were started, probably from pools of sodium chlorate and iron fillings that were scattered when the SCOG exploded. A far more serious incident could have occurred if other members of the crew had not taken prompt action to extinguish these fires.

Immediate Causes of the Accident On-board HMS Tireless

A number of theories were put forward to describe the causal mechanisms that might have led to the accident on HMS Tireless. One suggestion was that the explosive cartridge, which is used to initiate the SCOG reaction, could itself have ruptured the canister. However, testing showed that the blast generated by these devices was insufficient to cause such a failure. Water contamination was also discounted. Water ingress might have caused a potential accident through over-pressurization from the formation of steam as the SCOG reaction continued. However, the Board concluded that this could not result in the explosive fracture that was seen in the Tireless accident. Blocked vents might also have led to the rupture of the canister from a buildup of internal pressure. However, this also would not have had the force witnessed in the Forward Escape Compartment. Physical damage to the sodium chlorate block and manufacturing defects, including an increased concentration of iron filings, would not have increased the stored energy in the SCOGs to the point where the damage would be consistent with that witnessed on Tireless. It was concluded that the only ‘plausable’ cause was contamination of the sodium chlorate block by an organic liquid. In particular, oil contamination might have occurred while it was stored on a submarine. Unfortunately, it was not possible to be more precise about the source of such a problem; “due to the patterns of logistic management of… SCOGs, the SCOG that exploded may have been embarked and disembarked from many different submarines before its use in Tireless” (Ref. 6). Contributory factors included potential cracks in the sodium chlorate block and ‘constraints’ imposed by the location of the SCOG holder. These physical issues were, in part, the result of deficiencies in the ‘acquisition, manufacture, transport, storage, stowage and logistics management of the SCOGS’ (Ref. 6). Hence this incident provides many lessons that can be learned about the contexts in which degraded modes of operation can gradually erode the safety of military operations.

SCOG Procurement, Degraded Modes and Risk Assessment

In the late 1980s the UK Ministry of Defense formed the Submarine Secondary Improvement programme to increase the 3.5days of emergency oxygen that could be provided by existing oxygen candles. It was recognized that some rescue scenarios might require up to 7 days of oxygen. In consequence, a revised design was submitted to the MOD for a Self Contained Oxygen Canister producing approximately 30% more oxygen than the candles. However, the evaluation trial led to two incidents in which a prototype SCOGs caught fire and another ruptured from a build-up of internal pressure. In the mid-1990s, a revised design was submitted and this successfully passed the associated test programme. This was designed under the requirements of Joint Service Publication 430, a standard describing Ship Safety Management for the UK Ministry of Defense. A safety case was, therefore, developed from a range of hazard review meetings and workshops. The subsequent Board of Inquiry describes how the safety case assessed the contamination of a SCOG as “non credible due to design (‘non credible’ is described as ‘extremely unlikely to occur during the operational life of the unit’)” (Ref. 6). It did not consider the possibility of contamination during transport, handling and storage. However, documentation produced after the Safety Case did explicitly warn personnel of the potential hazards of contamination, including the operating document BR1326 Submarine Air Purification Manual and in Planned Maintenance Documentation. The safety case did not consider the potential consequences should a SCOG explode during operation. Consultations took place during procurement about whether the materials in these devices could constitute an ‘explosive store’ on board a submarine. However, the Defence Ordnance Safety Group rejected this by arguing that the Mk V oxygen candle, which it replaced, was not classified as an explosive. Self Contained Oxygen Generators were introduced on UK submarines in 2003. Similar devices have been supplied to Australian, French and US naval forces.

Previous SCOG Incidents and Tolerance for Degraded Modes of Operation

There is a long history of incidents involving devices similar to those involved in this accident. In the 1980s, the US Navy suffered two 'oxygen candle furnace fires' accompanied by explosions that were ascribed to hydrocarbon contamination of the devices. The Mir Space Station also suffered significant damage from the contamination of an oxygen generator; part of a latex glove was left inside the device during manufacture. However, degraded modes of operation are often characterized by a willingness to maintain levels of service even though crewmembers are aware of continuing problems with the systems that they operate. The Naval Board of Enquiry found evidence of a number of previous incidents involving the Self Contained Oxygen Generators on Tireless even during the deployment in which the accident occurred. These included a fire during which a continuous 4 inch flame came from the outlet ports shortly before the device was successfully ignited. The crew tipped the SCOG into a bucket of water until it was extinguished. 7 of the canisters misfired and were subsequently reignited. Another device continued to 'rattle' in its holder after being ignited.

An examination of the Navy's S2022 reporting systems found several incidents in which SCOGs had failed to ignite; recommendations focused on reducing the shelf life of the cartridges that were used to trigger the chemical reaction. The reporting systems also provided information about more serious incidents. These included fires on HMS Superb (January 2006) and two incidents on HMS Trafalgar (October 2004). The first fire on Trafalgar was especially serious because the canister became so distorted that it could not be removed from its holder. This hampered attempts to extinguish the flames. In the second incident during October 2004, molten materials began to drip through holes on another of the SCOG canisters on board Trafalgar. These incidents are significant because they show that crewmembers continue to entrust their lives to devices which have already failed. It also illustrates how multiple incidents can stem from problems that appear to be common across a batch of canisters. The manufacturer identified flaws in their production processes and recalled 294 SCOGs from four different production runs. All of these canisters were found on board the Trafalgar. 11 had already been used. The submarine was ordered to land all of these suspect SCOGS on return to the UK so that they could be withdrawn from service.

Following the incident on the Tireless, attempts were made to ensure that the SCOGs from these faulty batches had been destroyed. 103 were found in stored at Devonport naval base, 49 were still on the Trafalgar, 1 was on HMS Vanguard, 2 remained on HMS Tubulent, 1 was found in a dangerous waste store and 48 remained unaccounted for. The investigation also heard that around 1,000 canisters previously been sent back to the Hazardous Waste Store as being unfit for purpose. However, in November 2006 the majority had then being returned to the supply chain. This had taken some 6 months before the incident on Tireless. The decision to mark these SCOGs as serviceable was made following a visual inspection. These canisters were supposed to have a shelf life of 10 years on board a submarine and most were no more than 5 years old; "these events serve to demonstrate that the logistics management of SCOGs has been poor. It is possible, but cannot be proved, that a number of the unserviceable SCOGs recalled following the Trafalgar incidents were amongst the 550 … received by Tireless on 5th February 2007 prior to sailing for the ICEX" (Ref. 6).

There was also evidence that a number of previous SCOG incidents had gone unreported. This is significant because one of the critical problems in combating 'degraded modes' of operation is that operators may not understand the risks posed by equipment failures. They may be so accustomed to using 'work arounds' and other forms of coping strategy that they do not file incident reports. In consequence, higher levels of command may have little idea of the problems that occur during operational service; "precisely why submarine personnel are under-reporting is a matter of conjecture but it is the opinion of the Board that the S2022 reporting system has its shortcomings" (Ref. 6). Disillusionment and under reporting are characteristic of adverse event monitoring systems when staff receive little feedback or suffer long delays before their concerns are addressed.

The Logistics and Management of SCOG's in Degraded Modes of Operation

Submarines typically carry SCOGs for two different purposes. They are either stored for escape or for 'ready use'. Escape devices are stored in purpose built sealed lockers in the vessels escape compartments. They are not normally taken out except for an independent inspection conducted each year as part of the submarine's escape audit. After the accident, an inspection of these emergency SCOGs on the Tireless showed that they were intact and had not been damaged. In consequence, attention began to focus on the management of the 'ready use' devices. These were kept in the engineer's store and a forward naval store that had been fitted with appropriate fixed spray systems. The 'ready use' SCOGs were intended for operational situations such as under ice exercises. They were not stored in purpose built containers. In contrast, the cardboard packaging was often removed before they were stowed. Following the incident, it was determined that the Tireless carried more than 700 of these 'ready use' devices. A sample of 258 were inspected, of which 59 (23%) had been burned while the remainder had not been used. 147 (57%) had suffered some form of physical damage, 42 (21%) were not fully sealed, 71 (28%) showed signs of corrosion, 27 (11%) had suffered 'gross contamination' with either oil or grease (Ref. 6). The board concluded that Tireless and a number of other submarines will have been using 'ready use' SCOGs in a similar condition, posing a considerable risk to continued operations.

The opening sections of this paper argued that military personnel continue to exploit ad hoc 'work arounds' that enable them to maintain operations in the face of continued system failures. In the case of the Self Contained Oxygen Cannister's, these coping strategies can be partially explained by the lack of safety warnings on many of the devices. Screen printing techniques had been used to mark the SCOGs. Many of the warnings had been rubbed off through contact with other surfaces or with contaminants including water. These problems have been made known to the UK Marine Forces Marine Environment Survivability and Habitability group (MESH IPT) and remedies were sought to address the problem on remaining canisters. The subsequent enquiry traced the delivery of SCOGs back into the supply chain. It was found that the Naval Stores at Devonport provided a broadly appropriate facility for housing the devices after they had been delivered from the manufacturer. These were then delivered on demand to the submarines in the flotilla that needed them. However, 'their dangerous goods classification appears to have little or no impact on how they are transported to and from submarines' (Ref. 6). The subsequent investigation found that the canisters for the Tireless had remained uncovered on a jetty from the 5^{th} until 19^{th} February before being embarked into the submarine. While those for the HMS Vanguard had remained uncovered at Devonport for just under two years before being investigated by Explosives and Health & Safety Officers.

An important technique for reducing or mitigating the hazards created by degraded modes of operation is to provide staff with explicit opportunities to raise concerns about problems with the systems that they must operate. However, the only opportunity to reject SCOGs was when they were receipted after delivery to the submarine. No evidence could be found that this happened across the Navy nor were personnel trained to identify whether or not a canister was serviceable. The guidance that was available was ambiguous because it did not explicitly state the criteria for acceptance/rejection of the devices; "over the course of the investigation…, the Board has formed the view that complacency had set in since the introduction of the SCOG in 2003 and personnel were less cautious than they had been with the previous Mk V. oxygen candle. Despite the presence of warnings about the explosive risk presented by contamination with organic material there was no real experience or understanding within the MOD of just how violently a contaminated sodium chlorate candle could react" (Ref. 6).

Degraded Modes of Operation, Trust and Redesign

Previous sections have described how SCOGs were only used as a secondary from of oxygen generation. It was well known before the mission that the primary system would not work at depths shallower than 150meters because the electrolyser hydrogen discharge would freeze causing the system to trip. This concern was documented in a Fleet Publication Notice (FPN 27) and partly explains why Tireless had loaded additional SCOGs before leaving for under-ice operations. In other words, the crew and officers as well as many others in the Navy management structure understood that their electrolyser system would be operating in a degraded mode for long periods of the mission. The Board, therefore, questioned whether modifications could not have been made to extend the operating range of the primary oxygen systems. This, in turn, would reduce the reliance on these canisters and would have freed additional stowage to improve the care for the small number of 'ready use' SCOGs.

The Board of Inquiry argued that sodium chlorate technology continues to provide adequate protection for the crew providing that an assessment is conducted so that 'proper risk mitigation to prevent liquid organic contamination is applied to any future system'. If this is done then the board argues that any recurrence of the Tireless incident would be very unlikely (Ref. 6). They conclude that these technologies remain an acceptable secondary source of oxygen production for submarine operations; given that the associated hazards are no greater than those presented by other equipment on the submarine. However, this form of reasoning seems remarkably similar to the arguments that were used in favor of retaining the same explosive classification for SCOGs and Mk V Oxygen Candles. The SCOGs were no more dangerous than the candles. As we have seen, however, they exhibited different, more explosive failure modes during this accident. Further caveats can be raised about the continued reliance on sodium chlorate technology in missions similar to the ICEX. Previous sections have described the limitations of low pressure electrolysers. It might, therefore, be argued that sodium chlorate technology becomes the primary system when the electrolysers fall into degraded modes of operation.

The investigation report goes on to note that many submariners have become suspicious of SCOGs and that they are now unwilling to light them. In the aftermath of this incident, steps were taken to remove all of the existing design and replace them with a revised device. The Board also noted that it will be necessary to 'undertake a full internal public relations campaign, possibly including a change of name, before a reintroduction into service is considered'. These are significant observations; they reveal the consequences that arise when crewmembers understand the potential hazards from degraded modes of operation. It is regrettable that these dangers are often not fully realized until accidents have jeopardized the lives of many individuals.

Degraded Modes and Dimensions of Coping

As mentioned in previous sections, there is often a culture of 'making do' within many military organizations. Teams are encouraged to use their initiative to find 'coping strategies' that respond in flexible ways to unanticipated systems failures. The key argument in this paper is that individuals must be encouraged to raise concerns where if such failures create unnecessary risks that can ultimately jeopardize successful operations. The previous sections have focused on problems in the handling and procurement of Self Contained Oxygen Generators. However, these issues cannot be viewed in isolation. This culture of coping extends across multiple platforms and systems. For example, the investigation into the explosion and subsequent fires on Tireless found several other examples of applications where the crew worked hard to overcome design flaws.

Inadequate Emergency Breathing Systems: A number of coping strategies had to be deployed by the crew in the immediate aftermath of the incident. In particular, 25 personnel were forced to don breathing apparatus in the Forward Bunk Space as it began to fill with smoke and visibility was reduced to less than half a meter. They could have chosen to use self-contained Emergency Escape Breathing Devices. These were available and were specifically designed to allow escape from a smoke filled compartment. However, the formal investigation notes that these devices were relatively complicated and that crewmembers has 'a lack of confidence in it and an immediate preference to seek the Emergency Breathing System (EBS)'. This was a tethered supply that imposed more restrictions on crew movements around the nozzles where they could access the masks. These observations about the Emergency Escape Breathing Devices demonstrate that there are limits to the coping strategies that teams will employ – devices may be so complicated to operate that rather than find was of simplifying their use, individuals will look for alternatives such as the EBS masks.

The Emergency Breathing System masks were stored in lockers and these had to be emptied out before they could be distributed. Not only were there insufficient masks for all of the crew in the bunk space. There were not enough PCL (Pneumatic Components Limited) couplings for them to attach their breathing apparatus to the Emergency Breathing System. When access to the Forward Escape Compartment is closed off there is only access to 18 PCL couplings for the 35 crew who are located in the forward bunk-space beyond the 29 Bulkhead. In consequence, some of the crew were forced to use a 'buddy system' as they shared their masks. Others decided to crawl out of the compartment beneath the smoke. It was fortunate that the submarine officers determined not to close the 29 Bulkhead otherwise there might have been greater fatalities amongst those who were forced to cope with an inadequate number of marks and couplings.

This incident also revealed further problems with the Emergency Breathing System couplings. These concerns are important because they illustrate how degraded modes of operation may only be identified for some systems during extreme situations in which the crews are least prepared to devise coping strategies. There were two different designs for the PCL couplings. A more modern version required both hands to plug or unplug the user's mask. However, the older design only required one hand to make the connection. These differences were particularly exposed when personnel moved rapidly from one position to another in the vessel. In many situations, individuals who were carrying critical equipment had to put it down to disconnect the hose, move to their new location, put the equipment down and then reconnect before picking up the equipment again so that it could be operated. It is difficult to underestimate the additional workload that this created in cramped conditions with low visibility, especially when crewmembers had built up experience in the 'fleeting' one-handed operation of the older coupling devices.

Interactions between Degraded Modes and Training: The difficulty in connecting and reconnecting to the Emergency Breathing System were compounded by a lack of appropriate training. The detonation of the SCOG created a situation in which smoke rapidly accumulated in several areas of the submarine. The subsequent enquiry notes that "neither the pre-deployment training package nor general …safety training exercises a scenario whereby such a large volume of the submarine atmosphere is out of specification from the onset" (Ref. 6). This created a mismatch between the conditions that the crew had to respond to and their previous training – in other words the environment following the incident itself created a 'degraded mode' of operation that forced a range of coping strategies that had not been considered in training. For instance, standard emergency station actions focused on getting dressed and stowing loose gear. These actions were inappropriate, if not impossible, without first obtaining and then connecting their Emergency Breathing System masks.

Improvised Emergency Egress/Ingress Equipment: Other evidence of degraded modes of operation can be seen in the attempts that the crew made to open the hatch doors to the Forward Escape Compartment (FEC). These were buckled by the force of the initial explosion. It was critical to open these doors as the surviving crew members in the FEC struggled to put out fires that had been started by the material that had been propelled from the ruptured SCOG. However, members of the damage control team found it difficult to locate appropriate equipment that might be used to gain access; "to open the hatch doors to the FEC utilizing various pieces of equipment as improvised tools" (Ref. 6). There were insufficient crow bars and hacksaws the speed egress from the compartment. One reason for this is that the damage control scenarios used in training for submarine crews did not make as extensive use of these tools as they did in the surface flotilla. The rescue teams were forced to remove a ladder so that they could access the buckled hatch doors. Crewmembers managed to stand on drums and peer into the FEC where they could finally assess the extent of the injuries to their colleagues and also pass on information about the damage created by the SCOG. Some 44 minutes after the initial explosion, the crew managed to force one of the hatches in the opposite direction to the way in which it normally would have opened and then tore it from its hinges. The ladder was replaced and teams finally could enter the FEC.

Problems with Firefighting Equipment: Firefighting efforts were also hampered by equipment problems. A Self-Contained Firefighting Unit (SFU 90) was inadvertently deployed after the fires had been put out in the FEC. The crew struggled to divert the jet along 2-Deck and then directed it into the Junior Ratings bathroom. As individuals worked to stop the unit, the nozzle detached from the hose allowing water to flow freely. Although this might seem like a minor issue, it is important to reiterate that the crew were working in cramped conditions in breathing apparatus without many of the usual communications systems with reduced visibility. The failure of the nozzle was also important to the subsequent investigation because it had already been modified following a similar failure during a fire on HMCS Chicotimi in 2004 (Ref. 6). Fortunately, several of the crew on Tireless worked together to improvise a solution and put a kink into the hose that cut the flow while their colleagues isolated the supply on another deck. Once this was done, the unit was taken to the senior ratings' mess so that the missing nozzle could be repaired in case the unit was required again.

Communications Failures: Communications systems are essential in coordinating any effective response to adverse events, such as those that affected the Tireless. The failure of these applications creates two different sorts of problem. Firstly, crew members must find improvised solutions to restore contact with their team mates. Secondly, the lack of efficient communications channels also delays or frustrates attempts to coordinate a flexible response to other systems failures. Both problems are apparent in the aftermath of the SCOG incident. Immediately after the explosion, one of the crewmembers who was trapped in the Forward Escape Compartment (FEC) heard the telephone next to the Forward Escape Tower ringing but the handset was missing. He then tried to sue the handset in the canteen area at the other end of the FEC but this was broken. In such circumstance, suffering from disorientation after the blast, injured and still trying to fight the fires, he could not find a suitable 'work around' to communicate with other areas of the vessel. Eventually, he realized that there was someone calling to him from the other side of the buckled hatch.

The damage caused by the blast also illustrates other ways in which adverse events create degraded modes of communication. One issue was that the ward room filled with smoke and key officers (DCHQ2) had to move to the Switchboard Room. This created problems for other crew members who tried to relay information to them. Sometime later, an announcement was made using the main broadcast pipe that they could be contacted on telephone extension 234 so that a direct line could be established between the firefighting teams and their coordinators. In the meantime, crewmembers could not brief senior staff about the problems that they faced in opening the hatches to the FEC because the APL Cromwell VHF radio was not working. The Board of Inquiry later concluded that the incident demonstrated these devices were not fit for purpose. In this case, however, they were able to identify a ‘work around’. Rather than using the wireless system, they were able to use the SR Mess DC Net telephone system while tethered to the end of a 7.5m breathing hose. However, other members of the crew continued to try and use the Cromwell radio system even though it was inoperative. Further problems arose because pipes were inaudible due to the noise created by attempts to open the hatch and by the damage forward of the 29th Bulkhead. Again, the crew was forced to improvise communications channels and messages were relayed between officers and the fire fighting teams by word of mouth.

These examples show that systems failures can create the catalyst or trigger that exposes problems in many other applications. The damage created by the SCOG exposed problems in the storage and provision of emergency breathing apparatus. It also revealed the lack of appropriate tools for opening hatches. The initial explosion damaged primary communications systems. In each of these examples, crewmembers found ways to ‘work around’ limitations either in the design or provision of systems or from the damage caused by the incident. However, it is clear that these ‘ad hoc’, flexible responses may also have exposed individuals to considerable risk. If the decision had been made to respond to the flood alarm by closing the 29th Bulkhead then it is likely that more lives would have been lose from the lack of masks and couplings to the Emergency Breathing System. If the fire had developed then the lives of the fire fighters might have been in peril from the communications problems that characterize the passage of information by ‘word of mouth’ between different teams in high-stress situations.

Training Issues: Previous sections have associated degraded modes of operation with the failure of subsystems and of particular components. However, crewmembers in military operations are often forced to find ‘workarounds’ for breakdowns and ambiguity in doctrine and the chain of command. For instance, the Fleet produced a Training Directive for Under Ice training. This made extensive references to a capability training directive that had not yet been published. Hence, senior officers had to infer elements of the Pre-Deployment Training scenarios. Fleet also developed Command Guidance documentation for Under Ice operations. This arrived too late for the Flag Officer for Sea Training to use it in helping the crew of the Tireless prepare for their operation. The Submarine Support Integrated Project Team had reviewed previous materials used to prepare for ice missions. They had also assessed the previous guidance on environment impact. However, there was no coordinated safety review or risk assessment prior to the Under Ice deployment. In consequence, it was difficult for senior officers to determine whether or not the crew of the Tireless had sufficient training for the range of hazards that they might be faced with. A particular issue here is the need to maintain under ice expertise in a crew given that there may be significant intervals between these missions. Further problems were associated with the reduction in pre-deployment training from a maximum of 5 days down to 3 so that Tireless could return to HMNB Clyde for repairs. In this instance, not only did system failures force changes in the operational procedures on-board the submarine. It also forced the Flag Officer for Sea Training to improvise and find ‘work arounds’ in order to complete the necessary Pre-Deployment training within a shorter period of time.

Conclusions and Further Work

In many military operations, weapons safety is compromised by 'degraded modes of operation'. These are situations in which personnel are forced to find coping strategies that help them deal with the many different failures that complicate military life. In most cases, these ad hoc adaptations do not threaten safety. However, if these failures are not addressed they can gradually erode the barriers and other defensive measures that prevent casualties from occurring. We have illustrated these arguments be referring to a recent accident that led to the deaths of two members of the UK Royal Navy on-board a submarine. At the time of the incident they were participating in under-ice training. The mission formed part of wider tactical evaluations with the US military. Degraded modes of operation not contributed to the cause of this accident. Problems in the handling and storage of Self Contained

Oxygen Canister seem likely to have resulted in a ‘significant liquid organic contamination of the SCOG sodium chlorate block due to inadvertent ingress of oil inside the SCOG canister’ (Ref. 6). These handling practices emerged as a means of coping with the need to store large numbers of SCOG devices for ‘ready use’ when the primary because the primary oxygen supply relied on low pressure electrolysers that were liable to trip if ice formed in the hydrogen discharge piping. In other words, the incident stemmed from a fault in devices that themselves provided a means of coping with problems in the primary system for under ice operations.

Degraded modes of operation not only contributed to the cause of this accident but also complicated the response to the emergency. Crewmembers were forced to find numerous ways of coping with design flaws in their breathing systems. The Emergency Escape Breathing Devices were so complicated and difficult to use that teams preferred to use the Emergency Breathing System even though there were insufficient masks. Individuals also had to cope with numerous equipment failures – including the loss of the Cromwell VHF and the difficulty of hearing the piping system over the background noise in critical areas of the vessel. Further problems stemmed from the failure of fire fighting and rescue equipment, most notably when the nozzle of the SFU-90 system broke in a similar way to previous failures. In all of these instances, crew members were forced to adopt ad hoc solutions. The limited supply of Emergency Breathing System masks persuaded some crew members to crawl under the smoke while others shared their devices. The failure of communications systems forced teams to rely on word of mouth being passed along chains from command centers to the FEC. The failure of the SFU-90 nozzle was only rectified when team members put a kink in the hose to stop the water from causing further damage.

As we have seen, many of these ‘coping strategies’ had to be improvised in cramped conditions, with high levels of noise, low levels of visibility and significant quantities of smoke. It can, however, be argued that no crew will ever be ready for incidents of this nature. However, it is clear that significant steps can be taken to learn the lessons provided by the Tireless incident. Firstly, many of the limitations of the equipment mentioned above were well known. However, information was not always provided to those who needed it most – for instance about correct handling procedures for the SCOG devices. Secondly, there were significant weaknesses in pre-deployment training that left the crew unprepared for many aspects of this incident. These exercises had themselves been curtailed as a result of systems failures, which forced the submarine to return to HMNB Clyde. A key insight from this study is that we must reduce our tolerance to routine operational failures in many military operations so that personnel are more likely to rectify problems rather than accept the 'work arounds' that ultimately jeopardize safety. This applies to problems introduced in the acquisition of military systems, just as it applies to design failings, handling errors and even the planning of pre-deployment training.

References

1. C.W. Johnson and C. Shea, The Contribution of Degraded Modes to Accidents in the US, UK and Australian Rail Industries. 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, 626-636, 0-9721385-7-9, 2007.

2. C.W. Johnson and C. Shea, The Contribution of Degraded Modes of Operation as a Cause of Incidents and Accidents in Air Traffic Management. 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, 616-626, 0-9721385-7-9, 2007.

3. C.W. Johnson and C. Shea, A Comparison of the Role of Degraded Modes of Operation in the Causes of Accidents and Rail and Air Traffic Management. In 2nd IET Systems Safety Conference", The IET, Savoy Place, London, UK, ISBN 978-0-86341-863-1, 89-94, 2007.

4. United States General Accounting Office, Report to the Chairman, Subcommittee on Investigations and Oversight, Committee on Science, Space, and Technology, House of Representatives, Patriot Missile Defense: Software Problem Led to System Failure at Dhahran, Saudi Arabia, Februart 1992. Available on http://archive.gao.gov/t2pbat6/145960.pdf, Last accessed 11th June 2009.

5. C.W. Johnson, Act in Haste, Repent at Leisure: An Overview of Operational Incidents Involving UAVs in Afghanistan (2003-2005). In P. Casely and C.W. Johnson (eds), Third IET Systems Safety Conference, NEC, Birmingham, UK, 2008, IET Conference Publications, Savoy Place, London, 2008.

6. Board of Inquiry, Report of the Board of Inquiry into the Circumstances Surrounding the Deaths of LOM(WSM) Paul David McCann and OM(WSM)2 Anthony Huntrod on HMS Tireless on 20/21 March 2007. http://www.mod.uk/NR/rdonlyres/08A7D08E-E092-4159-94C3-9A26E182A01B/0/boi_hmstireless.pdf, Last accessed 11th June 2009.

Biography

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