CHAPTER 2

ENVIRONMENTAL CONDITIONS ANALYSIS

CONTENTS

1. INTRODUCTION

1.1 Environmental conditions are not strictly within the remit of the R&M function but they can have a fundamental impact on reliability, maintainability and ultimately availability. They must therefore be considered throughout all stages of a project.

1.2 Consider the following definitions from IEC 60050-191

"Reliability (of an item) is the ability to perform under *given conditions* for a given time interval"

"Maintainability (of an item) is the ability to be retained in or restored to a state in which it can perform as required under *given conditions* of use and maintenance"

Both refer to "given conditions" and it is these that are affected by the environment.

1.3 Environmental conditions can be natural, man-made or in some cases both. Table 1 shows a typical selection of criteria that could have an impact on the R&M of an equipment or system[1].

Natural	Man-made
Atmospheric pressure	Chemical
Cosmic (solar radiation)	Condensation (thermal cycling)
Electromagnetic discharge	Electromagnetic pulse (nuclear)
High temperature	High temperature
Ice	Icing (e.g. chemical processes such as use of liquid gases)
Low temperature	Low temperature (e.g. high altitude flight) or deep dive under water
Rain/humidity	Moisture
Shock and vibration	Shock and vibration (e.g. explosion and reciprocating machinery)

Table 1 Examples of natural and man-made environmental criteria

1.4 It is not uncommon to procure an item for use in one set of conditions and then expect it to perform as well under a new set of conditions. This was demonstrated during the Falklands War when the Rapier air defence missile

[1]For simplicity, in the remainder of the document, the terms"item", "equipment" and "system" will be taken to be interchangeable, unless otherwise stated.

system (designed to protect airfields in the temperate climate of Germany) were deployed to protect beachheads in the very much colder, salt-laden environment of the Falkland Islands! While procedures did exist that would have allowed the system to be used and maintained more effectively in this different environment, these were largely ignored because of the sheer pace of the campaign. Needless to say there were system reliability issues.

1.5 As we move towards more COTS solutions, the impact of environment becomes more relevant particularly in the area of IT hardware and electronic equipment in general.

1.6 The purpose of this chapter is to prompt consideration of environmental conditions and provide examples. While it is clear from Table 1 that items can be subjected to a wide range of conditions, this chapter will concentrate on some of the most common i.e. temperature, moisture, shock and vibration; electromagnetic influences. It is important to remember that these criteria do not work in isolation i.e. an item on an airframe is likely to be subjected to thermal cycling and vibration concurrently.

1.7 The 00-35 range of Defence Standards contains a wealth of information on various environmental effects, the means to mitigate against them and the type of tests that can be used to demonstrate compliance with the standard. They are therefore a very useful source of more in-depth information.

2. THERMAL CONSIDERATIONS

2.1 In the instruction book for an electronic appliance such as a DVD recorder, there is often a warning regarding the dangers of condensation (e.g.” if this unit has been subject to low temperature such as storage in a loft or garage, please allow it to come up to room temperature before switching it on”). Consider then, an item of avionics on an aircraft which is subjected to prolonged periods of very cold temperatures at altitude, before being subjected to temperatures of 40 degrees plus on the ground after landing. If the number of aircraft available is limited then equipment within those aircraft can expect to experience a considerable heating/cooling /heating cycle.

2.2 Such thermal cycling can cause damage to components and even the solder used to secure them, either directly, as described below, or by producing condensation which causes corrosion as discussed later.

2.3 Thermal fatigue is generally attributed to the differences in materials’ coefficient of thermal expansion (CTE) at the numerous interfaces. If an item is subjected to thermal cycling, the resultant relative movements as items expand and contract at different rates, sets up stresses at the interfaces which can cause cracks and delamination of the component, circuit board and encapsulating (or packaging) materials. It should be noted that the stresses and relative movements are both extremely small but when you consider that material on a semi-conductor is measured in 100's of nanometres (1 nanometre is 10^{-9} m) they are significant.

2.4 Thermal fatigue can also be blamed for other failure modes such as hermetic seal damage, die bond adhesion issues and breakdown of bonding wires with resultant open circuits.

2.5 The poor reliability of solder joints is also becoming an issue with the move to lead-free solders in response to the RoHS (Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment) EU Directive. In simple terms, lead-free solder joints are subject to increased growth of intermetallic compounds (IMC's) and these are propagated even more quickly under thermal cycling. Unfortunately, areas of IMC growth tend to be brittle, making them more susceptible to damage compared with the more ductile lead-based solders. Reliability of affected semi-conductors and electronic assemblies therefore decreases.

2.6 Such processes eventually manifest themselves at the equipment level as unreliability, which is why it is important to consider thermal range on operations, even if the equipment is not deployed to very hot climates. e.g. vehicles can be fitted with a range of electronic equipment which needs to operate correctly within a confined space. Over a protracted period, on a warm day, temperatures inside the stationary vehicle will climb rapidly with no possibility of using air conditioning if the vehicle is operating covertly. In such conditions, equipment reliability is likely to be affected.

2.7 Mechanical items can of course also be sensitive to extremes of temperature and Table 2 (from http://www.machinerylubrication.com) provides some examples

Bearings	Do not exceed 160°F (71°C).
Hydraulic Systems	Bulk oil temperature (at exterior of reservoir) should not exceed 140°F (60°C).
Gear Drives	Operate best in a range of 120°F to 140°F (49°C to 60°C). Keep in mind that an operating temperature rise of 90°F (50°C) combined with an ambient temperature of 60°F (15.6°C) will result in a total "oil operating" temperature of 150°F (66°C) in gear drives.
Gas Turbines	Oil temperatures should normally be in the range of

	130°F to 160°F (54°C to 71°C).

Table 2 Common mechanical systems and recommended operating temperatures

2.8 At the opposite end of the scale, very low temperatures can reduce the efficiency of machinery lubrication systems by increasing the viscosity of the lubricant which, for example, can lead to seized bearings. Prolonged exposure to very low temperatures will make some materials brittle and so selection of material to suit the environment is essential; which is why the hulls of ships that operate in extremely cold climates are made from a higher quality steel rather than basic carbon steel.

2.9 Low temperatures can reduce the elasticity of some materials such as those used for seals, with subsequent reduction in reliability and potentially serious safety implications – the Challenger space shuttle disaster was the direct result of launching the shuttle following a night of sub-zero temperatures and at an ambient temperature below the design specification of the critical booster motor "O" ring seals.

3. MOISTURE CONSIDERATIONs

3.1 Corrosion can be defined as;

"the destructive attack of a metal caused by either a chemical or an electrochemical reaction with the various elements in the environment"
This section will concentrate on the presence of moisture in the environment.

3.2 Items can be exposed to moisture either directly as rain, spray etc. or indirectly as condensation/humidity. Such exposure will usually trigger corrosion unless the appropriate protective measures are in place.

3.3 The British Computer Society have produced a paper (Ref A) on environmental range and data centre cooling and some of the lessons it contains can be read across to electronic installations within defence e.g.;
"High humidity is a major concern for IT equipment reliability as moisture ingress can damage key components within the server, particularly in combination with high temperatures."
or, from the same document;
"Frequent high IT intake humidity is known to cause a range of reliability issues for the IT equipment, <u>some of which accumulate over exposure time</u>."

3.4 Damage associated with moisture can take various forms. Moisture from condensation can adhere to the surface of a printed-circuit board (PCB), reducing the surface insulation resistance between pads or tracks; increasing leakage current and ultimately causing defective operation, seen as unreliability.

3.5 Moisture will also trigger corrosion and can lead to the growth of metal filaments between connector pins and between PCB tracks. If these filaments cause a short circuit they vaporise and so a cursory inspection of the “failed” PCB reveals nothing untoward, making fault diagnosis very difficult. Also, corrosion of circuitry, particularly with very fine pitch, can cause open circuits.

3.6 To reduce the problems associated with moisture at PCB level, components are often encapsulated or “potted” in a resin. However, the heat from soldering can turn any moisture already trapped in the component to steam and eventually lead to delamination and cracking of the resin (see Fig 1).

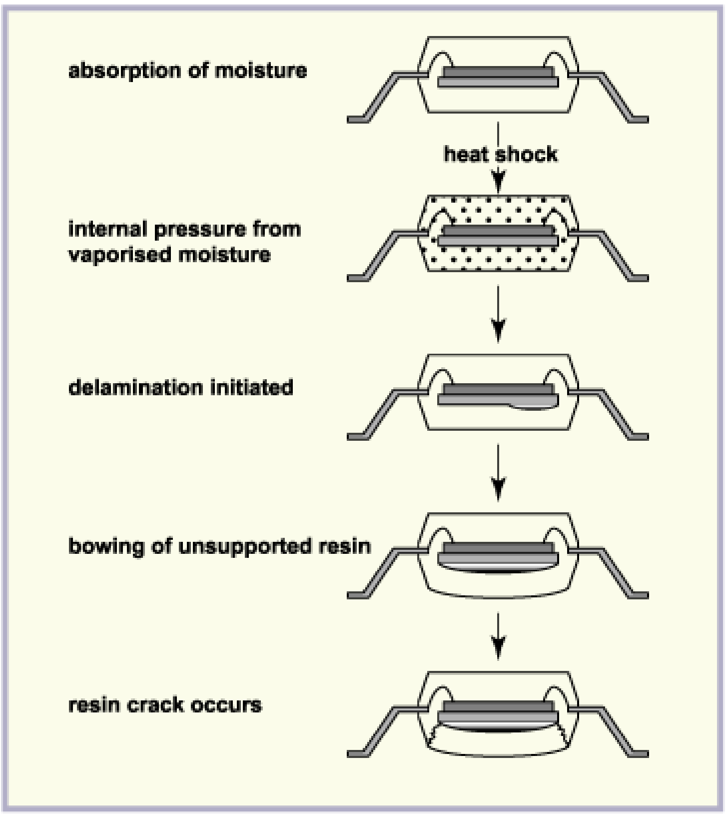

Fig 1 Moisture-induced crack generation and delamination model

3.7 Away from the microscopic world of PCBs and the like, moisture can cause serious corrosion whenever bare metals are exposed to water, particularly seawater.

3.8 Corrosion is a major problem on ships where there is no escape from a salt-laden wet environment and it’s presence creates a large maintenance burden. The presence of many dissimilar materials in such an environment only exacerbates the problem.

3.9 Structure can be severely weakened by corrosion, especially where it’s presence is hidden until the damage is serious, underneath equipment mounts for instance. The corroded surface of steel is porous and allows moisture to penetrate deeper until
eventually the material perforates. For this reason the designer should consider the feasibility of providing access for regular preventative maintenance. Also,

if the corrosion can be prevented at the outset by using cathodic protection systems on ships or appropriate coverings such as paint and sealing compounds on vehicles and aircraft, then the risks can be reduced or removed.

3.10 Corrosion of fittings such as threaded studs, bolts and nuts can make maintenance difficult and increase times to complete a task. This can apply across the domains e.g. upper deck fittings on a ship or wheel nuts on a vehicle.

3.11 Less obvious signs of corrosion such as rust pitting of precision-machined surfaces can cause serious problems as the corrosion material effectively expands and reduces clearances to the point where seizing occurs. This type of corrosion-related problem may be hidden and only reveal itself as a gradual reduction in equipment performance or decreasing reliability.

3.12 While ships probably experience the harshest environment from a moisture perspective, corrosion is just as much an issue on vehicles and aircraft. Indeed, whilst small holes or cracks caused by hidden corrosion of the steel hull of a ship may lead to a controllable leak into the ships bilges; undetected humidity-induced corrosion on an airframe travelling at high speed and altitude is likely to lead to catastrophic failure. Engineers therefore need to include sufficient drainage where appropriate or design out “moisture traps”. Maintainers also need to ensure that environmental seals in areas such as avionics bays are correctly fitted e.g. the appropriate curing times are allowed for the sealant material.

3.14 Given the high level of automation in modern military vehicles (engine management systems, software controlled steering etc.) the electronics also need to be protected from ingress of moisture.

4. SHOCK AND VIBRATION CONSIDERATIONS

4.1 Across the land sea and air domains, shock and vibration can cause direct or indirect equipment failures. However, shock and vibration are two different problems and must be dealt with in different ways.

4.2 Shock can be considered to be a single-pulse event such as the result of an underwater explosion or driving over a particularly deep pot-hole. Vibration is defined as

> “a continuous sine-wave motion, subjecting the product to continuously varying g-loads along one or more axes”.

4.3 A ship slamming in to waves or subjected to an underwater explosion will impart a shock to the equipment on board and potentially cause unseen damage and subsequent unreliability. The level of shock an item sees is dependent upon various factors including nature and size of initiating event and location of the item in the ship. Equipment is therefore usually shock-mounted or restrained in accordance with Defence Standard 08-120 and the type of mounting largely depends on the items tactical “importance”, e.g.

The item needs to survive a shock and continue operating if the mission is to continue – it is essential equipment. Full shock mounts are required but these only reduce the shock to 15g so the equipment must be designed to withstand such levels if reliability is to be maintained.

The item is not classed as essential but needs to be restrained to stop it becoming a “flying object” in a manned space or in a space where it is located next to essential equipment which could be damaged. The item could be fitted with simple brackets or even secure Velcro straps (often used for laptops in ships’ Operations Rooms).

4.4 A single shock event on a piece of electronic equipment is unlikely to cause screws to become loose within that equipment but vibration could do so. However, there is every chance that the same shock will cause any plug-in I/O cards to become unseated from their slots, causing a failure. The use of more secure locking arrangements for cards and fasteners can reduce the problem but not remove it completely.

4.5 A shock-mounted rack within a ship is designed to move within the constraints of the mounting used so it is important to take this into account when laying out equipment spaces; otherwise a rack under shock load could strike the adjacent rack and sustain damage leading to failure of both racks. In compartments such as Operations Rooms within modern warships, the equipment is mounted on a single raft to protect against shock which removes the need for individual shock mounts to be fitted on each equipment.

4.6 Manufacturers of COTS hard drives tend to assume their products will be used in a benign rack-mounted environment. If however, you decide to fit shock mounts on a drive to “protect it” when it’s fitted in the back of a vehicle, you are using the drive in an environment outside the designers specification and because the mounts allow some movement *the drive will move*; with unintended consequences! If the drive is subjected to a vibration with a frequency near its natural frequency, the drive will start to “absorb” energy and move an increasingly larger amount until physically stopped; usually by an adjacent component or structure. For this reason it is better to protect the complete equipment rack against shock and vibration rather than individual items within the rack. Incidentally, Solid State Drives do not experience the same head strike problems as older floating head drives but they are more expensive and so a cost/performance trade-off needs to be conducted.

4.7 One scenario to emerge more frequently in recent years is the use of COTS vehicles in a role for which they were not designed e.g. using a vehicle off-road that was designed for use on metalled roads. In one particular case, the vehicle experienced damage to wheels and axles from driving over rough terrain so these were strengthened. However, this led to problems with the suspension springs, so they too were uprated. However, the spring mounts were not designed for the larger, stiffer springs and so they subsequently started to fail. The vehicle was therefore unreliable, more difficult to maintain than originally planned and was eventually re-designed.

4.8 Apart from shock, equipment can be subjected to constant background levels of vibration from the many pieces of rotating and reciprocating machinery within the aircraft, ship or vehicle.

4.9 Vibration can cause components within electronic equipment to resonate and so fail as a result of the constant back and forth movement of the connections with the circuit board. While it is possible to provide vibration damping systems, these can be complex and expensive with no guarantee of success unless the designer knows the range of vibrations the equipment is likely to experience during its operational life. One way to mitigated movement under vibration is to put adhesive between the component and the board to reduce the movement.

4.10 Sometimes the actual circuit board material is not stiff enough and so it flexes, putting stress on all the solder joints and producing intermittent faults. These will often be regarded as "No Fault Found" back in the repair shop because the vibration source is not present.

4.10 The most severe vibrations are probably seen inside rotary wing aircraft, usually helicopters. Vibration levels in helicopters are typically four to seven times that experienced by fixed wing aircraft. For that reason, nuts and bolts used on airframes or aero engines tend to be wire locked.

4.11 Helicopter vibration control is a complex subject but broadly speaking there are three areas which need to be considered;

Rotor dynamics (number of blades, shape of blades, shape of blade tips)

Fuselage dynamics (structural design, location of heavy parts)

Choice of appropriate anti-vibration device (active, semi-active or passive)

4.12 The difficulty in tracing the source of unexpected vibration in an aircraft is one of the reasons that Health and Usage Monitoring Systems (HUMS) are widely used in the aviation industry to give warning of impending mechanical failure. The data produced can also be useful when looking for reasons for poor reliability of equipments.

5. ELECTROMAGNETIC CONSIDERATIONS

5.1 Electromagnetic Interference (EMI) consists of any unwanted, spurious, conducted or radiated signals of electrical origin that can cause unacceptable degradation in system or equipment performance. EMI can originate from man-made or natural sources. Figure 2 (from http://www.emcuk.co.uk) gives an illustration of the problem and while the diagram is land-orientated, the principles apply within aircraft, ships and vehicles.

5.2 Sources of man-made EMI include radio and radar transmitters, power lines, fluorescent lights, car ignition etc. Natural sources include lightning, radioactive decay of certain materials in the ground and solar influences. Some of the plastic moulding compounds used to encapsulate electronic components to protect them from environmental damage contains isotopes which emit low-level alpha radiation which themselves can cause damage.

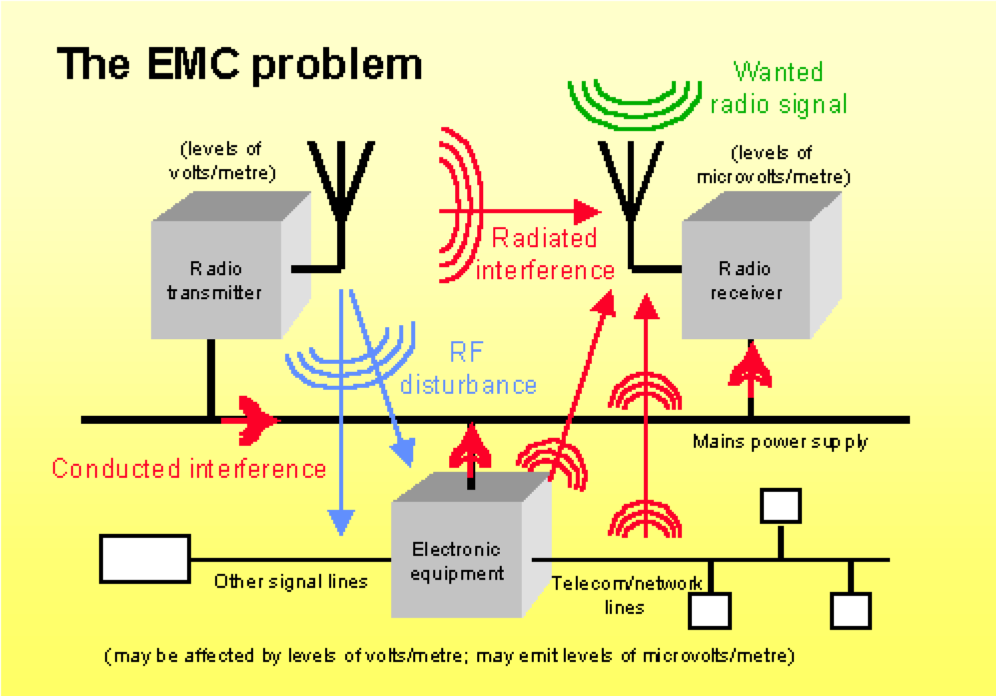

Fig 2 - how radio transmitters can interfere with electronic systems, and how electronic systems can interfere with radio reception

5.3 The electromagnetic impact of CME's (Coronal Mass Ejections or solar flares) and the like cannot be ignored and indeed some civilian flight paths which routinely cross the Polar Regions are diverted at times of high solar activity. Electromagnetic activity caused by the interaction of the incoming charged particles and the earth's atmosphere can affect some electronic components. Also, high-energy neutrons are produced which penetrate the atmosphere and can interact with semi-conductors at ground level to produce random failures in everyday applications. For instance, Field Programmable Gate Arrays (FPGA's), which are widely used in electronic systems, are susceptible to the influence of these neutrons and so need to be suitably "hardened" if their reliability is to be maintained. (Ref B)

5.4 As land vehicles begin to routinely incorporate engine management systems and the like, they too will need to consider electromagnetic activity and not just that in the natural background. There is anecdotal evidence of EM problems associated with the use of 12V "lighter sockets" in COTS vehicles. Some installations of military communication systems have been credited with causing "undemanded activity" in other systems before the EMI issues were properly addressed.

5.5 The trend to fit many different electronic systems to vehicles for use in theatre means that EMI must be considered; it is not unknown for a new piece of equipment to be installed too close to an existing emitter. The new equipment may then seem unreliable even though closer analysis would show its performance is good when the adjacent legacy emitter is switched off.

5.6 The “fly by wire” approach to modern aircraft control systems means that spurious EM emissions can be extremely dangerous. Between 1981 and 1987, the US Army lost five Black Hawk helicopters, resulting in numerous fatalities and injuries, because the on-board flight control systems were not sufficiently screened against High Intensity Radiated Fields around radio broadcast masts.

6. CONCLUSIONS

6.1 Whenever R&M are being specified, the environment must be considered, i.e. Could the environment impact on this equipment in such a way as to cause it to fail and so reduce its reliability and consequently availability?
Could the environment impact on this equipment by making maintenance more difficult, thereby increasing maintenance times and consequently reducing availability?

6.2 Known or potential changes of operational environment need to be considered early on in order to avoid problems of incompatibility such as those experienced in the Falklands, Iraq and more recently, Afghanistan.

6.3 While the impact of the environment needs to be considered, it is usually necessary to trade any mitigation against cost, time, performance and safety.

LEAFLET 0

REFERENCES

A. BCS Paper entitled "IT environmental range and data centre cooling analysis(Assessment of the impact of IT inlet temperature and humidity ranges on data centre cost and overall energy consumption)" dated May 2011

B. Paper produced by Microsemi "FPGA reliability and the Sunspot Cycle" dated September 2011

LEAFLET 1

THE IMPACT OF ENVIRONMENT AND TERRAIN ON RELIABILITY

There are many definitions of reliability; the following is from IEC 60050-191

"Reliability is the ability to perform *under given conditions* for a given time interval."

All too often the conditions under which Defence materiel is expected to operate are not properly factored into the original requirements. This can lead to poor equipment reliability in service.

The following leaflets attempt to explain why such an approach is fundamentally flawed.

LEAFLET 2

IMPACT OF ENVIRONMENTAL AND TERRAIN ON EQUIPMENT RELIABILITY - LAND

CONTENTS

1 INTRODUCTION

1.1 There are many reasons why military equipment is unreliable; these can include poor design and using equipment beyond the agreed performance thresholds e.g. increased vehicle weight due to application of armour. However, since mechanised warfare began, one of the biggest contributors to unreliability of military equipment in the Land domain has been the environment and terrain in which it is operated.

1.2 Consider the following statements from a report which considers tactical mobility in Afghanistan, The Falklands and the Gulf (Ref A)

> *“Mobility across the bogs was difficult. A lightly loaded Land Rover could barely cover 4k in an hour and had to avoid the numerous knolls and stones." Each vehicle had to be careful not to follow in the tracks of another vehicle to avoid sinking into the earth where the other vehicle had broken through the thin crust of the bog. Once a vehicle had broken through the crust, the earth becomes an impassable muck. Vehicles*
>
> *loaded with ammunition or towing anything could not move at all.*
>
> *“Few highway systems exist that are comparable to the US interstate system. Much of the limited road networks are simple macadam highways barely wide enough for two-way traffic and lacking any shoulders. Virtually no roads existed in areas where the major offensive operation would occur. Vehicles and tracks would have to traverse through deep sand, rock, wadis, dry lakes and river beds. Little to no man made or natural features exist to guide movement.”*

1.3 This short paper will consider the impact of environment and terrain on Land equipment.

2 THE PROBLEM

2.1 Recent conflicts have identified shortcomings in the reliability and performance of military equipment because of the environment and terrain in which they have been tasked to operate.

2.2 To assist those procuring defence equipment there is Defence Standard 00-35 “Environmental Handbook for Defence Materiel” (parts 1 to 6) which addresses the various types of man-made and natural environment that equipment can expect to be exposed to, based on the planned areas of operation. The table at Annex A, reproduced from the standard, provides the range of climate categories and details of each. However, to simply specify a category for testing within the SRD may not be sufficient and thought must be given to the actual environment an equipment will be exposed to.

2.3 For example, an item of electronic equipment, procured under the UOR process for use in-theatre, is fitted low down on the outside of a vehicle due to lack of space. It is likely to have been tested for exposure to vibration, dust penetration and high temperatures (but see below). The vehicle it is mounted on will have a known fording performance but the new equipment may not have been tested for immersion in water as the current theatre is seen as “hot and dusty”. Immersion in water while crossing water could therefore be sufficient to render the electronic equipment unreliable at best. The test specification therefore needs to reflect this.

Also, the 00-35 series of standards do not consider terrain for land vehicles and there is currently no terrain standard.

2.4 Environment - temperature

2.4.1 Equipment that was originally procured for use in Northern Europe will have passed the appropriate range of environmental testing but when subjected to more extreme conditions in theatre, reliability has often decreased. Typically, the most severe temperature testing for equipment used in Northern Europe would have been climate category A2 (see Annex A). However, the current area of operations i.e. Afghanistan, falls within the climate category A1 and so overheating problems are not uncommon.

2.4.2 If the ambient air is hotter than the equipment was originally designed for, cooling systems are less efficient, therefore there is an increased risk of overheat, engine damage and ultimately equipment failure.

2.4.3 Other less obvious potential triggers of unreliable performance, associated with high temperatures include;

> Batteries require additional maintenance as they do not hold their charge efficiently in intense heat.
>
> Ammunition in direct sunlight can reach a temperature where changes to the chemistry of the components renders them inaccurate or even dangerous.
>
> Electronic equipment such as radios and laptop computers can overheat and become unreliable.
>
> High temperatures are detrimental to rubber and so tyres become more prone to punctures from sharp rocks. Tracked vehicles experience faster wearout of the track material.

2.4.4 At the other extreme, experience in the Falklands thirty years ago showed that many equipment controls such as switches were virtually useless when wearing Arctic mitts in the icy temperatures of the South Atlantic.

2.4.5 Also, some power packs, designed for use in Northern Europe became unreliable in the low temperatures as the coolants and lubricants being used were found to be unsuitable.

2.4.6 The Rapier air defence system was designed to protect airfields in Northern Europe but when deployed in the Falklands its reliability dropped because it was being used to protect landing sites on and around beaches and so was exposed to a cold, salt-laden damp environment. Such an environment did not suit the electronics and also prompted rusting of steel components.

2.4.7 Equipment designed for use by Royal Marines world-wide faired better in the Falklands because it’s original planned area of operations included Arctic warfare and so it will have been tested to prove survival in a wider range of climates.

2.5 Environment – Sand and Dust

2.5.1 Sand and dust are a significant problem and during the first Gulf War in Iraq, a lot of equipment succumbed to the clogging of air intakes with sand and more recently, the very fine dust typically found in Afghanistan is said to permeate everything. Incidentally, wet weather does not bring much respite in Afghanistan because the fine dust creates a very sticky mud which, when it dries out, sets like concrete. Apart from making progress by troops and wheeled vehicles difficult, the mud coats exposed components such as flexible transmission gaiters and boots, which become rigid when they dry out and then fail under normal levels of vibration.

2.5.2 Clogging with sand and dust can damage turbochargers, air coolers and potentially vehicle power packs through overheating. Ingestion of fine dust and sand can also disable pneumatic systems which are used to control suspension and brakes in some off-road vehicles.

2.5.3 Fine dust will permeate electronic equipment, particularly if the item has a cooling fan which draws dusty air in. Any filters that are provided can quickly block and the equipment overheats. If the intake is blocked to remove dust ingress, the item will probably overheat anyway. The best solution is to use such equipment in clean conditions in the shade whenever possible.

2.5.4 Sand can also cause degradation of the optical surface of weapon sights which become scratched when wiped. When sand and dust are combined with lubricant, they can cause serious malfunctions, as was the case with the SA80 rifle.

2.5.5 Ironically, there are times when the solution to one problem can trigger another. An example of this is when side skirts were first fitted to Challenger Main Battle Tanks during the 1st Gulf war to try to reduce the sand and dust which was being kicked up by the tracks and then drawn into air intakes at the rear of the vehicle. The skirts worked but after a fairly short time some tanks were losing tracks for no apparent reason when operating at low speeds in soft terrain. RMCS trials showed that there was a build-up of debris between the drive sprockets and the skirts which, during slow speed manoeuvres, was forcing the track off the sprocket and also damaging the skirt (Ref B). The skirts were subsequently re-designed and currently there are various designs of flexible skirts fitted to the side-mounted armour introduced for use in theatre.

2.6 Terrain

2.6.1 Driving off-road can cause damage to vehicles, particularly if that vehicle is operating at or above its designed maximum weight. As weight increases, perhaps by the fitting of additional armour, the vehicle sits lower on its suspension and ground clearance is reduced. This can lead to front idler wheels or sprockets of tracked vehicles "bottoming out" on particularly rough terrain or at the base of inclines.

2.6.2 Wheeled vehicles can suffer suspension damage for the same reasons e.g. earlier variants of Mastiff experienced failure of suspension springs and axles because while they performed well in Iraq they were being used on roads and the change to off-road use over-stressed key components.

2.6.3 Experience in Iraq has indicated that even driving on metalled roads is not without problems and many vehicles sustained wheel damage as they experienced kerb-strike while trying to cross between carriageways which were strewn with barricades and battle debris. More recent wheeled vehicles are designed to withstand a far higher degree of kerb-strike and in some cases a complete wheel station can swiftly be changed in the event of damage.

2.6.4 Mountainous terrain such as that currently found in theatre, brings its own difficulties with steep inclines to negotiate and often loose road surfaces on unmade roads. Such terrain makes movement slow and convoys more vulnerable. To counter this, some allied forces have introduced all-terrain vehicles that can negotiate 45 degree slopes but manoeuvrability is often gained at the expense of protection or speed.

2.6.5 Even within the relatively benign environment of UK training areas there can be terrain-related issues e.g. the high flint content of some chalky areas has damaged the rubber tyres of tracked vehicle road wheels and there is always the threat of getting bogged down if a vehicle leaves the marked tracks.

2.6.6 One of the most important design drivers for vehicles intended to be predominantly driven off-road, is the performance in two types of soil i.e. sandy or soft clay. However, vehicle performance in soft clay soils is likely to be more critical than in sandy soils because of the reduced friction and hence increased probability of lack of traction and forward power.

2.6.7 The main factors affecting the soft soil performance of a wheeled vehicle is its weight, the number and size of the wheels/tyres and the tyre's deflection. (Ref C). One way of overcoming changes in soil type when operating wheeled vehicles is to alter the tyre pressure e.g. reducing the air pressure within the tyres will increase ground contact area, reduce ground pressure and so make traversing soft ground much easier. (Fig 1) While this has been done manually in the past, newer wheeled vehicles often include some kind of CTIS (Central Tyre Inflation System). This enables the driver to select from a range of pre-determined pressures such as "Road", "Track" or "Emergency", depending on the prevailing situation. CTIS systems can also be used to maintain pressure in the event of a slow leak or small puncture in a tyre.

Fig 1 – Mercedes Benz vehicle with CTIS showing effect of decreasing tyre air pressure

3 THE WAY FORWARD

3.1 The best way of ensuring that a piece of equipment will do what the user wants it to do is to procure that equipment against a robust set of requirements. As previously stated, there are standards which contain definitions of various climate categories, and the recommended ways of verifying that a design meets those requirements but no standards currently exist which adequately define terrain and so terrain requirements for vehicles tend to be limited to wading depth, trench crossing capability and "ability to operate off-road".

3.2 Work has been done recently by MOD contractors which identifies the need for a terrain standard and further work is ongoing (Q4 2013) to produce such a standard.

3.3 With the drawdown in Afghanistan and the movement of some equipment into core programme it is worth noting that equipment procured under the UOR process for current operations in "hot and dusty" environments is likely to need further environmental testing to prove its suitability to be operated world-wide, if it is selected to be part of the core programme.

4 REFERENCES

4.1 Report ADA262627 – "Lessons in Combat Service Support Tactical Mobility: The Afghanistan Conflict, Falklands War and Operation Desert Shield/Desert Storm" Army Command and General Staff College Fort Leavenworth 04 Feb 1993.

4.2 Challenger 2 Mobility and Track Durability Trial (incorporating the Albert Jaeger step trial).

EGW Div, RMCS Shrivenham 10 September 1999.

4.3 Platform Design Aspects of Tactical Mobility.

QinetiQ/FST/CR032193/2.0 November 2003.

ANNEX A

Table 1 Definitions of Climatic Categories CATEGORY	APPLIES TO:
A1 - EXTREME HOT DRY	Areas which experience very high temperatures accompanied by high levels of solar radiation, namely, hot dry deserts of North Africa, Western Australia, parts of the Middle East and central Asia including parts of the Indian sub-continent, and parts of South Western USA/Mexico.
A2 - HOT DRY	Areas which experience high temperatures accompanied by high levels of solar radiation and moderately low humidities, namely, most of Australia, most of the middle East and Central Asia, most of the Indian sub-continent, most of the North African continent and parts of the South, South West USA, North Mexico, parts of the South American Continent and the most Southern parts of Europe.
A3 - INTERMEDIATE	In strict terms, this definition applies only to those areas which experience moderately high temperatures and moderately low humidities for at least part of the year. It is particularly representative of conditions in Europe except the most Southern parts, Canada, the northern United States and the southern most part of the Australian continent.
B1 - WET WARM	Areas which experience moderately high temperatures accompanied by continuous very high relative humidity. These conditions are found in rain forests, and other tropical regions during periods of continuous cloud cover, where direct solar radiation is not a significant factor. Geographical regions covered include the Congo and Amazon basins, South East Asia including the East Indies, the North coast of Madagascar and the Caribbean Islands.
B2 - WET HOT	Areas which experience moderately high temperatures accompanied by high humidity and high direct solar radiation. These conditions occur in exposed areas of the wet tropical regions, such as the coastal region of the Gulf of Mexico, Northern Australia, and Eastern China.
B3 - HUMID HOT COASTAL DESERT	Areas which experience high temperatures accompanied by high water vapour content of the air near the ground in addition to high levels of solar radiation. These conditions occur in hot areas near large expanses of water such as the Persian Gulf and the Red Sea.
C0 - MILD COLD	In strict terms, this definition applies only to those areas which experience mildly low temperatures such as the coastal areas of Western Europe under prevailing maritime influence, South East Australia and the lowlands of New Zealand. However for the purposes of this standard, this definition is considered to apply to all land masses except those designated as Category C1, C2, C3 or C4.
C1 - INTERMEDIATE COLD	Areas which experience moderately low temperatures such as central Europe, Japan and central USA.
C2 - COLD	Colder areas which include northern Europe/Scandinavia, the prairie provinces of Canada, Tibet and much of Russia.
C3 - SEVERE COLD	The coldest areas of the North American continent. The coldest areas of Greenland and Siberia.
C4 - EXTREME COLD	

M1 - MARINE HOT	The tropical bulk sea areas where high ambient air temperature is the predominant climatic characteristic.
M2 - MARINE INTERMEDIATE	The warmer, mid-latitude, regions of the seas, particularly temperate sea areas where high humidity combined with moderately high temperatures are together the principal climatic characteristics.
M3 - MARINE COLD	The colder regions of the seas, particularly the Arctic zone where low ambient air temperature is the predominant climatic characteristic.

Table 2 Extreme Temperatures in Climatic Categories Highest temperatures		**Lowest temperatures**	
A1	58°C	C0	-26°C
A2	53°C	C1	-42°C
A3	42°C	C2	-56°C
M1	51°C	C4	-68°C
M3		-38°C	

Table 3 Additional Climatic Factors and Related Categories CLIMATIC FACTOR	**CATEGORY AFFECTED**
Atmospheric pressure Wind Ozone Hail	All Categories
Blowing sand and dust Rain Drip hazard	A1, A2, A3, B1, B2, B3, M1 and M2
Ice accumulation Snow loading	C0, C1, C2, C3, C4 and M3
Temperature of surface sea-water Sea states	M1, M2 and M3

LEAFLET 3

ENVIRONMENTAL FAILURE MODES WITHIN THE MARITIME DOMAIN

CONTENTS

1 BACKGROUND

1.1 This paper looks to identify systemic issues in the maritime domain, where equipment issues and / or failures are directly or partially attributed to its environment i.e. 'Environmental Failure Modes'

1.2 It is publically reported that the primary causes of engineering disasters are usually considered to be due to one of the following:
Human factors; Design/Manufacture flaws; Materials failures; Extreme conditions or environments; Combinations of these reasons.

1.3 The Royal Navy suffer from environmentally induced failures, many of these failures are due to the inadequacies of the design. Whilst some of these failures can be attributed to requirements creep during design, many of the failures are caused through poor definition of the environment the equipment will have to successfully operate in.

1.4 Predicting the environment any Defence equipment will have to operate in throughout its life is extremely difficult. e.g. climatic change, sea states etc.

1.5 Maritime Equipment is particularly difficult i.e. a Frigate may take 5 – 10 years to design and build and be in-service for a further 25-30 years. During that long period of time, the threat, role and operating requirement(s) are likely to change many times, all having an impact on the environmental conditions it may experience e.g. .radiation, thermal, acoustic, vibration, toxicity, shock, stress and many more.

2 POLICY/GUIDANCE

2.1 There is ample documentation available within MoD or the public domain on the effect equipment failures have on the environment. However, there is very little guidance on environmentally induced failures i.e. where the environment is directly or partially responsible for the failure of equipment. The lack of guidance makes it extremely difficult to determine the best method of exposing any vulnerabilities associated with the environment.

2.2 Def Stan 00-35: "Environmental Handbook for Defence Materiel" is a useful suite of policy documentation. It contains 6 parts covering the following subject categories:
Control and Management; Environmental Trials Programme Derivation and Assessment Methodologies; Environmental Test Methods; Natural Environments; Induced Mechanical Environments; Induced Climatic, Chemical and Biological Environments.

2.3 Def Stan 00-35 explores a range of alternative environments equipment may face, how to test for them and prove compliancy. Part 6 Section 9 specifically looks at Deployment or Installation on Surface Ships.
It also gives specific guidance on temperatures and humidity experienced across the globe. It offers some crude environmental factors and guidance temperatures for different operating scenarios e.g. Naval Sheltered / Unsheltered, Ground Benign / Fixed / Mobile etc.
Whilst this guidance material may assist in de-risking the effects of environment on equipment, risks are still apparent i.e.

- Localised environmental conditions e.g. the effect of mating/adjacent equipment having environmental impact on each other (see next section for examples of this)

- Change in requirement, as detailed in the previous section.

3 ENVIRONMENTALLY INDUCED FAILURES

3.1 History has proved many defence programmes have been subject to equipment failures caused directly/partially by its operating environment. The remainder of this chapter captures some of these experiences to highlight some of the pitfalls the Royal Navy has endured.

- A control panel was forced to shutdown non-essential systems on a Maritime platform due to the lack of power available. This operational disruption resulted in extensive investigation to determine the root cause of the malfunction. The root cause was attributed to the poor performance of the maritime engine (supplying the power) whilst operating in high ambient air temperature.

The issue described above was the result of the environment directly causing equipment to fail. It is not just the surrounding environment the equipment operates in, that causes failures of this type. Sometimes a poorly designed platform may cause localised environmental issues i.e. one part of a ship causing differential temperature on another.

- Maritime equipment is reported to have suffered water impact. The equipment was test for water impact at a downward angle (simulating rainwater). Reality proved the equipment was subjected to water impact from below in an upwards direction. This was caused by a combination of seawater spray and impact from pre-wet nozzles, which ultimately caused a loss of performance.

The above experience highlights the need to understand localised environments, which may be addressed when conducting a design integration assessment. This inevitably addresses any physical interfaces / tolerances etc but may also review environmental impacts on adjacent/mating equipment.

- Frigate designed for use in North Atlantic, was deployed to the Gulf. Air Conditioning Plants could not cope with high ambient temperatures and failed. Onboard conditions were appalling with air temperatures of up to 40 degrees C. Maintainers repeatedly repaired the air conditioning.

Equipment was expected to operate in environments it was not designed for. Designers should not just consider the environmental conditions we currently operate our equipment, but what can be expected throughout an equipment's life. It is critical that a realistic mission profile is created, that identifies:
ALL environments equipment will have to successfully operate in, and
MOST LIKELY environments equipment have to successfully operate in.
Operators equally need to be aware of their responsibilities for operating within agreed specifications/tolerances

- Multiple Ships in the Royal Navy Fleet have entered a sandstorm environment for prolonged periods, this has inevitably resulted in sand ingestion of engines which has gradually degraded the engine and ultimately resulted in engine failures

This is another example where equipment is being operated in an environment not originally designed for. If equipment designers were aware of its intended use/environment, it is possible this environmental weakness may have been designed out.

- RFA was operating in Northern Latitudes when a cold mass air descended (below minus 20 deg C). Ship detected temperature drop and attempted to close 'forced air vent' (FAV) supplying heating matrix to maintain onboard temperature/heated water. Isolating the FAV caused pipes to freeze/rupture and the heating matrix to fail.

The failures were caused by slow reaction of the temperature drop (it required an immediate isolation of FAV and closure of external damper) in combination to an inadequate heating matrix design i.e. no anti-freeze in the water.

- LSD(A) operation in Arctic conditions caused the failure of Upper Deck Fire Main, Air Treatment Units (ATU), Domestic Hot Water and degraded propulsion cooling.

It was discovered that the LSD(A) was operating in conditions outside the original design specification (9 Deg C below endorsed operating temperature). The LSD(A) did not undertake First Of Class cold weather trails due to budgetary constraints. It was subsequently recommended to amend the ship design by fitting an extra boiler and fitting electrical heating elements to the ATU's / Chilled Water Plants (CWP).

- Control and Data Collection Units (CDCU) overheating in moderate/high ambient temperature. Redesign to divert venting for increased air flow in cabinets, coupled with permanently pinning cabinet doors open prevented these failures.

The CDCU had insufficient ventilation / cooling, ambient air temperature contributed to excess temperature generated by the equipment itself. Integral fan was subsequently fitted preventing failures of this kind

- Multiple accounts of sand contamination on a Maritime Platform whilst operating in the Gulf e.g.
    - Air Treatment Unit (ATU) suffering sand contamination to filters and intake assemblies, creating increased maintenance burden.
    - Sand impregnates grease and lubricant coatings on Replenishment At Sea (RAS) assembly, which acts as a grinding paste on RAS wires rope cores reducing service life.
    - Direct Ventilation intakes distributes fine sand to compartments (Main Engine rooms, generator rooms etc) which significantly deteriorates paint

coatings/fabric of the compartments. This also creates unnecessary maintenance burden to rectify.

The fine sand experienced whilst operating in this region of the world created both reliability issues and surplus maintenance / husbandry routines. This highlights the importance of distinguishing the exact type of environment e.g. ‘fine’ sand, quantified by perhaps using particle counts / measures.

3.2 Listed below are ‘example’ scenarios/questions that highlight other areas to consider when thinking about environmental implications on equipment to be used in a defence programme.

- Will the stability of the electrical supply from the Gas Turbine Assembly have any affect on the equipment it supplies
- Will the vibration / resonance on the ships hull have any affect on COTS (Commercial Of The Shelf) based equipment.
- Will the ship movement (pitch, yaw, roll) have any lasting damage to fixings/brackets on equipment.
- Will the high levels of sea/air salt cause corrosion on equipment not designed to operate in that type of environment

4 MISSION PROFILE

4.1 Fundamental issues may occur when deriving a Mission Profile:

- MOD may specify them incorrectly/insufficiently.
- Industry may misinterpret ill defined requirements and design equipment not fit for purpose.
- Royal Navy invariably use their equipment in different ways and in different places to those which we originally thought we would.

4.2 It is imperative MoD provide Industry with an accurate mission profile to enable them to design and manufacture equipment fit for purpose now and in the future. This requires the authority to determine the range of environments the equipment is likely to face throughout its life, without setting unrealistic and unlikely high tolerances that will escalate the cost of production.

5 REQUIREMENT SETTING

5.1 The previous section explained the importance of compiling a realistic mission profile equipment will operate. It is equally important this information is suitably translated into a set of requirements that are simple. The requirements must be unambiguous and clearly state what environment the equipment will operate in. Recognising of course, the equipment may be subjected to different environments throughout its life. The requirements should quantify what level of environmental impact e.g. temperature range, sea states etc, the equipment should be able to successfully operate in (bearing in mind the conditions may change over time).

5.2 Equipment reliability on COTS products needs to be considered as they will be designed to operate in less harsh environments that a Defence programme may be subjected.

5.3 The previous paragraph referred to the level of environmental tolerance that is acceptable on Maritime equipment. The acceptable level should be defined using 'failure definitions' that determine if equipment has either failed or suffered degradation of performance. This can be achieved by ensuring the requirements make reference to some form of performance characteristic.

6 CONCLUSION AND RECOMMENDATIONS

6.1 This guidance paper has captured a broad depth of 'Environmentally Induced Failures' experienced in the Royal Navy and Royal Fleet Auxiliary. There are a number of underlying causes for the incidents above, but they essentially fall into two categories:

Poor Design / Manufacture
Poor requirements definition / specification.

6.2 It is imperative that a robust set of requirements are recorded that details the environment the equipment should successfully operate in through life.

6.3 In deriving the requirements, there will be Value for Money trade-offs i.e. if an equipment is designed for extreme / volatile environment(s) this will increase the unit production cost.
At least one of the Environmentally Induced Failures referenced above may have been prevented if suitable Trials Programme had been carried out. This may have given opportunity to address the issue and minimise the operation impact in-service.

6.4 This progressive acceptance can be illustrated with an example of a warship's radar. Initially Factory Acceptance Tests (FATs) would be performed on the radar to determine that it functions in a benign environment with readily available test facilities. Once the manufacturer was satisfied it worked in this environment it would be integrated on to the warship (or a major element of it) and Harbour Acceptance Trials (HATs) would take place. Ideally the HATs would repeat a subset of the FATs. Recognising of course, the effects of some environmental conditions take many years to materialise and would be extremely difficult to replicate this experience through dedicated trials.

6.5 The environmentally induced failures experienced on Defence Programme listed in this document highlights the extent environment can have on equipment, if a type / level of environment is not anticipated. The probability of these types of failures occurring can be reduced by considering what environment(s) equipment may be subjected to throughout its life.

6.6 There are many considerations personnel should consider that may influence or be directly attributable for environmental failures, such as:

- Where in the world will it be used, stored, transported?
- What are the conditions in these places?
- Will there be any environmental controls? Air conditioning, vibration, isolation etc.
- What happens if / when the environmental controls don't work?
- Will current conditions still apply at end of service life? – used in different places, climate change.