GICHD

GUIDE TO THE AGEING OF EXPLOSIVE ORDNANCE IN THE ENVIRONMENT

Cover: An F1 hand grenade with a UZRGM-2 fuze, weathered after 17 years ageing in the field. The fuze is no longer functional although the thick metal casing, while corroded, has remained intact.
Image: Roly Evans.

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GLOSSARY OF TERMS

The following terms and abbreviations are used in this report:

ABS Acrylonitrile Butadiene Styrene

ALANFO Aluminized Ammonium Nitrate Fuel Oil

Alloy A mixture of metals, composed in order to have characteristics unavailable from a single metal

AN Ammonium nitrate

AN-AL Aluminized Ammonium Nitrate

APB Ammunition Process Building

Arrhenius kinetics
The Arrhenius equation is a formula for the temperature dependence of reaction rates

ASA Ammunition Storage Area

AXO Abandoned explosive ordnance

CISR Center for International Stabilization and Recovery

Composition A substance incorporating a physical mixture of compounds and/or elements

Compound A substance in which the elements are chemically combined

DB Double-based: propellants based on NC and NG

DPA Diphenylamine

EMI Electro-Magnetic Induction

EO Explosive ordnance

ERW Explosive remnants of war

GP Gunpowder

GWHF Golden West Humanitarian Foundation

HE High explosive

HME Home made explosive

HMX Cyclotetramethylene-Tetranitramine

IED Improvised explosive device

IM Insensitive Munition

IMAS International Mine Action Standards

JMU James Madison University

NC Nitrocellulose

NG Nitro-glycerine

OB Open Burning (disposal technique)

OD Open Detonation (disposal technique)

PBX Polymer bonded explosive

PETN Pentaerythritol Tetranitrate

RDX Cyclotrimethylenetrinitramine

RSP Render Safe Procedure

SAA Small Arms Ammunition

SB Single-based: propellants based on NC

TATB Triaminotrinitrobenzene

TB Triple-based: propellants based on NC, NG and nitroguanidine

UV Ultra-violet (light)

UXO Unexploded explosive ordnance

INTRODUCTION

Explosive ordnance (EO) ages from the point of manufacture. Even when stored in ideal conditions, ordnance will age and therefore it has a service life, typically up to a couple of decades. Some elements of explosive ordnance age more quickly than others. For example, propellant has a finite life span due to its stabilizers degrading over time, especially in hot conditions. Ordnance that remains after a conflict, including explosive remnants of war (ERW) and mines, will not only age, but age according to the environment within which it is left. Invariably, ordnance left in the elements will age more rapidly than that in storage.

Ageing of explosive ordnance is relevant for the conduct of demining, battle area clearance (BAC) and explosive ordnance disposal (EOD) operations. This is for three main reasons. First, the risk posed by the ordnance can change over its lifespan. For example an item fuzed with a cocked striker might see its holding devices age and fail prior to the ageing and failure of the coiled spring of the striker mechanism. At some point this can make the item even more dangerous to touch and move before the fuze becomes fully non-functional. Second, how easy it is to detect the metallic components of an item, especially a mine, changes as it ages. Typically ferrous components become harder to detect as they corrode. Third, the appearance of explosive ordnance, especially mines, can change significantly as they age. Correct identification of any item of explosive ordnance is essential to dealing with it appropriately. It is for these reasons that those who come into contact with explosive ordnance should know about how it ages and what implications this has for finding and destroying it.

The risk of explosive ordnance that has aged in the environment can be easily misunderstood. While the potential for an item to function as intended probably diminishes over time as the fuzing system may deteriorate, this should never be mistaken for an absence of risk. Items of explosive ordnance such as artillery projectiles and mortar rounds are designed to withstand extreme forces on firing. Thick steel casings are also designed to provide fragmentation on detonation. High explosive encapsulated in steel is very resilient if undamaged on impact, and can potentially remain intact in the environment for not only decades, but as ammunition from World War I proves, over a century. While the means of initiation might no longer be functional, the encased high explosive remains a significant hazard that poses an ongoing risk to EOD operators and civilians.

Abandoned explosive ordnance (AXO), Iraq. These unfuzed 130mm artillery projectiles have had their copper driving bands removed. Image: Roly Evans.

The aim of this guide is to give an overview of what is currently known about the ageing of explosive ordnance and the changes in risk that this presents to EOD operators. Analysis of ageing requires internal examination of the ordnance, a highly technical process sometimes referred to as 'exploitation'. A brief introduction to exploitation is given in Chapter 1. Different explosive ordnance with differing designs have different predispositions to ageing; this is explained in Chapter 2. How various environmental factors affect the components of explosive ordnance is covered in Chapter 3, more specific changes are detailed in Chapter 4. Such changes can alter the risk that explosive ordnance presents and this is discussed in Chapter 5. Two case studies, one for World War II landmines found in the Netherlands and Denmark, and another for ERW from the same period in the Pacific, add to the many examples from the field included throughout this guide.

The guide focuses mainly on conventional land-based and air-delivered explosive ordnance. General discussion of ageing effects on improvised explosive devices (IEDs) is included. Although water is a key factor in the ageing process, ammunition designed specifically for underwater use, such as torpedoes and sea mines, is not studied. While much of the detail is relevant to how items age in storage, and some examples given show items that have aged in storage, this is not the particular focus of this guide. The guide also identifies gaps in the understanding of ageing and point to some potential future research. There is plenty that remains unknown about this extensive subject.

A British 6-inch artillery projectile with the copper driving band removed found close to the old German front line of August 1916, near Guillemont, Somme, France in December 2021. Note that the projectile is in remarkably good condition. Explosive ordnance that is made to withstand extreme forces on firing, and whose casing is designed to produce fragmentation, are resilient, especially in clay soils with higher pH values, and pose a long term hazard. Image: Quentin Naylor.

CHAPTER 1
ASSESSING EXPLOSIVE ORDNANCE

The condition of explosive ordnance may be readily apparent from its appearance. If it appears to be badly damaged or heavily corroded, it is probably in a poor state of repair and unlikely to be fully functional. However, this is not always the case. The internal condition of the ordnance may not always conform to its external appearance. Superficial exterior corrosion may give the impression of substantial deterioration when the internal components have actually been well protected and are still functional. Conversely, a resilient casing material may remain in reasonable condition, while masking the deterioration of more vulnerable components inside. In order to assess the true state of an item of explosive ordnance, and ascertain the effects of ageing, more thorough investigation is needed. This means a form of disassembly, often done remotely, to gain access to the internal components, sometimes referred to as exploitation.

Exploitation is a highly specialised task, often requiring dedicated equipment and an intimate knowledge of the ordnance. Such work is a form of ammunition processing and should be conducted in accordance with International Ammunition Technical Guidelines (IATG). For permanent facilities this means designated ammunition process building (APB). Such work may also be carried out in temporary field facilities. In both cases, the explosive processing facilities should conform to risk reduction process level (RRPL) 2 within IATGs.[1]

A Mechanical Remote Fuze Disassembly Kit (MRFDK) used for removing small energetic components such as primers in fuze rotors, Golden West Humanitarian Foundation GWHF Cambodia 2014. Specialist explosive processing facilities, whether permanent or mobile, may be needed to fully ascertain the effects of ageing on explosive ordnance. Image: GICHD.

Before any such work can be undertaken, a detailed risk assessment should be conducted. This should consider every potential hazard that may arise, not only from individual energetic components but also from mechanical elements such as coiled springs and striker assemblies. The risk assessment should detail specific controls for each risk identified. It can be used to guide the explosive process used to disassemble the item.

Although some ammunition has the provision for disarming or maintenance, most is not designed to be disassembled. Items that must withstand significant forces on firing, or for aerial bombs significant forces in flight, and also employ fragmentation as the main lethal mechanism, will invariably have a thick steel casing. Such a casing can not only protect the internal components of an item of explosive ordnance but also mean access requires specialised remote cutting tools, such as drop saws. Even if the casing can be opened in this way, with the risks carefully managed, manual approaches, possibly after soak periods, may be required to reposition the item for further cuts, or to disassemble internal components. The condition and sensitivity of the munition and its subassemblies is often unknown until physical inspection. X-ray is also a very useful tool for assessing internal components, but is not always available and sometimes cannot provide the same detail as disassembly.

The ultimate way to establish the functionality of explosive ordnance is to test it under operational conditions but since this would usually involve detonation, this is often impractical. First, the destructive power of most munitions means that any test rig is likely to be damaged or destroyed; second, it is unlikely that a suitable platform (i.e. aircraft, gun or launcher) would be available to deploy the weapon safely, or under controlled conditions.

A portable cutting deck, operated by the Golden West Humanitarian Foundation in Vietnam. Access into thick-cased munitions, such as mortar bombs, projectiles and air-dropped bombs, can be achieved using commercial bandsaws, which are adapted for remote operation and observation. This is a specialist task but, performed properly, allows even the largest ordnance to be sectioned and examined internally. In this instance a Vietnamese soldier from Technology Centre for Bomb and Mine Disposal Engineering Command (BOMICEN) sets up a cut on a Mk-82 General Purpose Bomb. Image: Fenix insight Ltd.

A cut on a Russian 152mm OF-540 high explosive artillery projectile at the Golden West Humanitarian Foundation (GWHF) specialist processing facility in Cambodia. The projectile casing and pressed TNT fill are in good condition and have not been subject to significant ageing in the environment. Image: Roly Evans.

It is, however, sometimes possible to test only critical components of the weapon. For this, the main charge is usually removed, to eliminate the larger part of any potential detonation. A fuzing mechanism, detonator or even the explosive train up to the booster, can sometimes then be separated so that it can be tested as an assembly in its designed configuration.

An improvised explosive test rig in the Falkland Islands/Malvinas. During this operation, landmine fuzes were first separated from their main charges, substantially reducing the explosive hazard, and therefore the safety distance. Using remote operation and observation, a weight was dropped onto the fuze to see if it would function. The rig was sufficiently strong to withstand the detonation of the small amounts of explosive within the fuze. Image: Fenix Insight Ltd.

The process of complete disassembly, examination and testing (along with preliminary studies, risk assessment, etc.) is typically only conducted by specialist organisations and is well beyond the competencies taught in conventional EOD training.

ENDNOTES

1 United Nations Office for Disarmament Affairs, *International Ammunition Technical Guidelines*, "07.30: Ammunition processing operations Safety, risk reduction and mitigation," Third Edition, 2021: 5.

CHAPTER 2
PREDISPOSITION TO AGEING

The design and construction of explosive ordnance naturally has a significant impact on how it ages. Generally, ammunition that is designed to be projected or dropped and undergo significant forces will have robust casings that can prove in some senses remarkably resilient. Items left out in the open over years may quite quickly become unserviceable for firing, but nevertheless remain to some degree functional. Explosive ordnance that is placed rather than dropped or fired, such as certain mines, tend to have much less robust casings and therefore may tend to age more quickly. There are exceptions. Mines that are designed to produce fragmentation such as some bounding mines, may be very resilient. Some blast mines with plastic casings, that are well designed and manufactured, may also prove remarkably robust.

Various mines in the same environment show different ageing characteristics. The relatively thin plastic cased TM-62P3 anti-vehicle mine shows rupture of the casing, possibly accentuated by the effect of prolonged exposure to ultraviolet (UV) sunlight. The thicker cased MVP and MVCH mine fuzes seen on the right are more resilient, albeit their colour has bleached in the sun. The OZM-72 bounding fragmentation mine on the left shows discolouration of the protective paint but has broadly withstood the ageing process well. Image: Roly Evans.

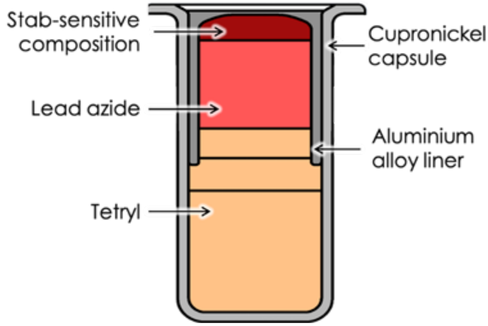
ENERGETIC COMPONENTS

PRIMARY EXPLOSIVES

Primary explosives are the types that are used mostly in primers and detonators; they are more sensitive to heat, shock and friction than 'secondary' explosives (used for main fillings) and tend to be less chemically stable. Some of the primary explosives used in detonators are prone to decomposition that may lead to a chemical reaction with surrounding materials.

Mercury fulminate, which is used in some older igniters and detonators, forms relatively stable compounds when it degrades. However, tetracene (used in newer igniters) can decompose in the presence of moisture and heat (>60 Celsius) to form more sensitive primary explosive compounds, such as 5-azidotetrazole.

Lead azide $Pb(N_3)_2$ is a primary explosive commonly used in military ammunition. A decay product of lead azide (hydrogen azide, HN3) can react with metals such as copper, zinc and cadmium, or their alloys, to form highly sensitive explosive compounds.[1] This is one of the reasons why the primary explosives may be pressed into an aluminium liner before incorporation within the outer detonator capsule, made from a material such as cupro-nickel alloy. If the detonator capsule is breached the subsequent entry of moisture can lead to the formation of hydrogen azide. Alternatively saturation of primer compositions that include lead azide and lead styphnate can potentially lead to reduced functionality, possibly temporarily. This was suspected to be a cause of stab detonator failure in anti-personnel mines in the Falkland Islands/Malvinas. Functionality testing of detonators extracted from 50 P4B mines removed from four locations on the islands, including a mines dump, found that only 16 (mostly from the mines dump) produced any explosive effect.[2] Many mines had spent more than three decades in at least partially saturated peat.



An example of a typical older munition detonator (in this case, a Russian MG-201). Under certain conditions, the protective aluminium liner can degrade, allowing moisture to enter the detonator. At this point, the lead azide decays to form hydrogen azide gas, which may then react with nearby metals, including the exposed cupro-nickel detonator capsule, to form highly sensitive explosive compounds. Tetryl is used less and less due to its toxicity. Image: Fenix Insight Ltd.

SECONDARY EXPLOSIVES

In general, the military high explosives used in main fillings and boosters are remarkably stable and resilient. 2,4,6-trinitrotoluene (TNT) from World War I, and Composition B from World War II, are still recovered in good condition, with little significant deterioration or evidence of reaction. There may be very minor decomposition, but any differences in performance during detonation are usually insignificant. A notable exception is picric acid, more correctly known as 2,4,6-trinitrophenol (TNP). Like TNT, picric acid is a nitro aromatic. It was used as a booster and high explosive filling during World War I and World War II but was found to react with certain metals to produce highly sensitive explosive compounds.[3]

A Vietnam-era 155mm United States M107 projectile, recovered in Quang Tri province and cut open for analysis in 2018. The Composition B filling, which is a mixture of RDX and TNT, shows virtually no sign of deterioration over the 50 years or so since it was manufactured. Most of the military high explosives used in main ammunition fillings are extremely stable and resilient even when the casing has deteriorated. In this case the casing has protected the main explosive fill remarkably well.
Image: Fenix Insight Ltd.

PROPELLANTS

Propellants are used in rocket motors, and the charges that fire projectiles and mortars. Many are double-based propellants containing nitro-glycerine (NG) and nitrocellulose (NC), which are reasonably stable, but begin to decompose after a few years, particularly if subjected to high temperatures. A simplified technical explanation for this is that as "the chemical ageing of propellants starts with the homolytic breaking of the weak O-NO_2 bond of the aliphatic nitrate esters (nitrocellulose NC and nitro-glycerine NG), thus forming nitrogen dioxide and the corresponding alkoxyl radical."[4]

The NG/NC compositions used in propellants usually contain stabilisers to slow the degradation process, but these stabilisers themselves only remain effective for a limited period (generally in the order of 20 years).[5] After this, significant changes can occur within propellants. In the open, particularly in hot climates, propellant becomes dry and brittle. Where it is exposed to human activity, this runs the risk of initiation through ignition (such as a dropped cigarette) or friction. Exposed propellant is far more vulnerable to ignition than most secondary high explosives and is frequently the cause of fires in ammunition depots.

An ammunition depot in Iraq, 2003. Looters seeking brass cartridge cases have tipped unwanted double-based propellant out onto the ground, where it becomes dry and brittle in the hot sun. In this state, propellant is highly vulnerable to ignition by heat and friction. Image: Fenix Insight Ltd.

In sealed containers, as most rocket motors are, the nitrogen dioxide gas generated by the decomposition of the propellant remains trapped, and results in increased pressure within the vessel. This, in turn, accelerates the break-down of the propellant, so that the reaction accelerates. If left unchecked, this can lead to spontaneous ignition or explosion in a process known as 'autocatalytic initiation'. Several major stockpile explosions have been attributed to this phenomenon.

MATERIALS

The materials used in a munition are selected primarily for their ability to perform a particular role reliably. Reliability includes not only the functionality of a mechanism, but also sufficient robustness to withstand extended periods of storage, transportation, handling and deployment. The munition must be capable of enduring adverse conditions during these phases, and must remain safe at all times.

As long as these criteria are met, then cost, availability and ease of manufacture may become important factors in the selection of materials. Coatings and treatments may also play a significant part, since a relatively cheap but vulnerable material may perform adequately if it is suitably protected. For example, mild steel is painted, coated or plated to provide adequate protection for the anticipated life span and uses, rather than using a more expensive and less malleable 'stainless steel' alloy.[6] This is the same in most manufacturing industries, where the design is specified to meet or slightly exceed the requirement, rather than being 'over-engineered' at far greater cost. This is also true of explosives and other energetic materials. Function, safety and reliability are usually the key factors, but only within the bounds of the planned lifespan and expected conditions. Materials used will have been selected for compatibility and stability within designed operating parameters, but once these are exceeded or compromised, unexpected chemical reactions and physical changes may occur.

Unexploded or abandoned ammunition left in the environment will be subjected to conditions well outside its intended design specification, and far beyond its intended lifespan. Physical changes might include excessive shrinkage or expansion due to extremes of temperature, leading to the rupture of a casing or the cracking of a cast grain. Chemical changes might include decomposition, with the evolution of gaseous products that might increase internal pressure, or the production of compounds that then react with other compositions. A 2019 GICHD study of aerial bombs and artillery projectiles found in Vietnam concluded that "in addition to changes within individual components, such as rusting of steel or hardening of rubber, materials may react with one another to create unforeseen chemical effects."[7]

A P4Mk2 anti-personnel mine on the jungle floor in Sri-Lanka. The plastic casing is relatively resilient. The sandy soil drains quickly. Many mines found here were still viable. Image: Roly Evans.

Thin plastic containers used to contain aluminized ammonium nitrate have split easily after less than a year, Kobane August 2015. Thin cased plastic containers will invariably rupture if they contain an explosive mixture such as aluminized ammonium nitrate due to the changes to crystal structure caused by temperature cycling. Plastic of any thickness is especially vulnerable to damage from UV light over time. Image: John Montgomery.

CHARACTERISTICS

The single most important characteristic for a material used as a casing for explosive ordnance is its thickness. In inert materials, the majority of chemical ageing effects (such as corrosion) occur at the surface. Relatively little activity occurs deeper within the material, because it is protected from the chemical influences that cause the changes. In a material prone to corrosion or other chemical change, this means that vulnerability is linked to the ratio of surface area to mass. The thinner the material is, the more likely it is to degrade quickly, and the thicker the protective layer, the more slowly it will corrode. Experiments on aluminium oxide film in 2011 showed that thicker oxide films were more resilient to corrosion.[8]

Given that the surface area reduces only very slowly as the material degrades, it might be expected that the process would proceed at a relatively steady rate. However, another important effect – particularly with metals – is the build-up of an oxide layer. The oxidised material on the surface often provides an additional barrier to the ageing influence, resulting in the process slowing down.[9 10]

Similar characteristics are seen with other metals, including steel, although these characteristics vary substantially between different alloys (such as mild steels versus stainless steels), which are also influenced by their crystalline structures. “Stainless steel is a blanket term that covers a wide range of corrosion-resistant metals. The degree of corrosion resistance depends on the elemental makeup of the alloy. The specific chemical resistance varies with the metal’s chemistry as well. The key mechanism of corrosion resistance in stainless steel is the formation of a chromium oxide passive layer on the surface that provides excellent corrosion resistance.”[11]

While aluminium will corrode to form a protective oxide film, and stainless steel a chromium oxide layer, iron oxide does not tend to provide the same protection. “Iron corrosion results in a reddish-brown, flaky, powdery substance (hydrated iron oxide) called rust, which does not act as a stable barrier of protection against further corrosion. As the hydrated iron oxides layer forms, it repeatedly flakes off instead of adhering to the substrate’s surface, thus leaving the substrate prone to continued electrochemical reactions involving further corrosion in the presence of oxygen, moisture and other pollutants.”[12]

A BLU-26 explosive submunition found in Lao PDR. The steel alloy components can be seen by the difference in corrosion around the clamp ring join of the submunition and the ball bearing fragmentation beneath the main aluminium outer casing. The outer casing has an aluminium oxide layer that corrodes slower than steel alloy. This item has been on the floor of a primary jungle for over four decades, albeit on high ground with good drainage. While it is certainly weathered, the resilience of the casing is nevertheless evident. Image: Roly Evans.

The casing of an unexploded M107 projectile, recovered around 50 years after it was used in Vietnam. A section through the projectile shows the surface is heavily corroded, although the steel beneath is in remarkably good condition. Under some circumstances, a superficial iron oxide rust layer may provide protection that slows down the corrosion process. Image: Fenix Insight Ltd.

Copper alloys, including bronze and brass, are also used in ammunition and also show corrosion resistance. Bronze "is a copper alloy whose major alloying element is tin. It is specifically suited to applications that come into contact with seawater. When small amounts of silicon are added to the alloy, the corrosion resistance is significantly improved." [13] Brass "is a copper-zinc alloy and is extremely common. The addition of small amounts of tin to the alloy also increases the overall corrosion resistance of this alloy whereas ever-increasing amounts of zinc will decrease the corrosion resistance. Brass also has a lower melting point than pure copper or bronze."[14] The overall result is that the same material can be quite vulnerable when it is thin, but robust when used in thick layers. The rate of degradation can also change significantly, with superficial corrosion proceeding quite rapidly, but slowing as a protective layer of oxidised material builds up. In the case of iron, the degree of protection offered by surface oxidation may depend on other factors, such as whether the rust is held in place and absorbs, or is coated by, another surrounding material, such as clay. In the open, even thick rust may not provide any significant barrier to further corrosion.

A British 4.5 inch artillery projectile near Thiepval, Somme France, January 2023. The rotating band and copper fuze adaptor for the Fuze No. 44 show how resilient copper and copper alloys can be despite prolonged exposure in the environment for over 100 years. The layer of clay soil has very likely also helped to preserve the projectile. Image: Quentin Naylor.

Thickness of plastic is also a consideration, even if the plastic employed in the construction of a landmine is largely resistant to corrosion, such as polyolefins or polyvinyl. Both groups exhibit good chemical resistance properties, even to solvents. Acrylonitrile butadiene styrene (ABS), a resilient thermoplastic polymer, is also used for the casing of some minimum metal plastic mines. (ABS is more commonly known as the plastic used to make Lego). Other forms of polystyrene, sometimes rubberised, are also used, as is bakelite. All plastic cased ordnance are especially vulnerable to UV energy from the sun causing a photochemical effect within the polymer structure. While plastic mines are vulnerable to ultra-violet damage if exposed over time, mines buried can be remarkably durable in form. Extreme heat can also damage plastic casings.

A PRB M3 mine in northern Chad. The mine was buried and had thus been largely protected from UV light. In this instance the high temperature has caused a split in the polythene mine casing. The bakelite fuze assembly has on the other hand remained intact. Different plastic materials age at different rates even in the same conditions. Bakelite is a remarkably resilient material that is even difficult to penetrate with thermite torches. Image: Fenix Insight Ltd.

Wood, once used for mine casings, is the least resilient material to weathering in the environment. Used as a temporary expedient, as well as a means of minimising metal content, wooden casings rarely last more than a few years even if treated. Wooden stakes for omni-directional mines will also rot within a few years, leaving the metal components vulnerable to more rapid weathering on the ground.

The Russian PMD-6 box mine, as it appears intact. The PMD-6 has a wooden case that was judged to be adequate for its expected short service life. It was never intended or expected to remain functional for years. Image: GICHD.

The effects of ageing on the materials of a Russian MUV-2 fuze, used in a PMD-6 anti-personnel mine, buried more than 30 years ago in Cambodia. The wooden casing of the PMD-6 has long since rotted. Image: Fenix Insight Ltd.

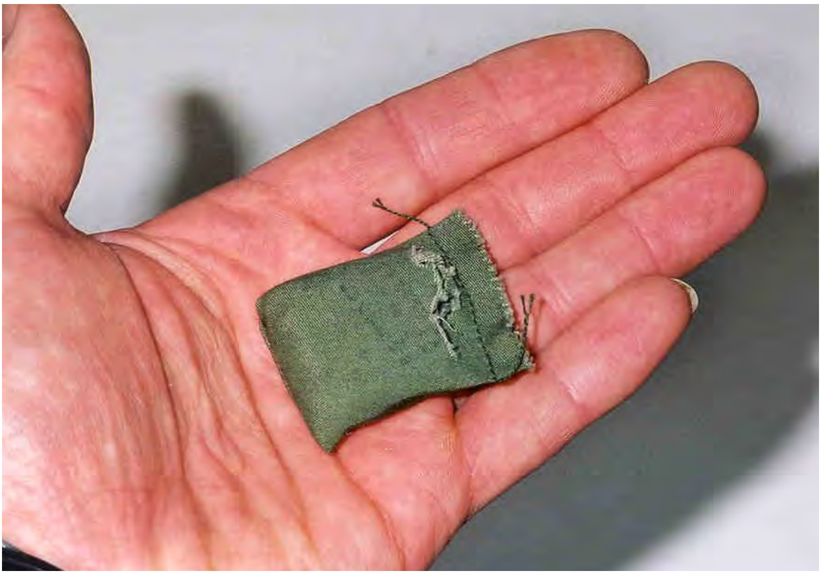
1: a thick steel section shows rusting, as expected
2: the plated steel of the fuze body remains largely uncorroded
3: the thin aluminium detonator capsule has corroded away completely at this point

A wooden-cased Holzmine laid during World War II that survived intact in the sand dunes of Skallingen, Denmark. Mines above the water table could remain intact if sufficiently enclosed with sand. Image: Martin Jebens, Danish Coastal Authority.

DESIGN AND PRODUCTION

The design and method of production can significantly affect the vulnerability of a munition. Each piece of ordnance will be designed with a role, a lifespan and its expected environment in mind. If the lifespan is expected to be short, and the environment protected, then longevity may be a very minor consideration.

For example, the gravel mines, used by the United States of America in the Indochina Wars, were stored, transported and deployed from sealed dispensers filled with Freon; once deployed, they were only intended to function for a matter of days. A cloth casing was therefore adequate, and the explosive was deliberately selected to self-neutralise after prolonged exposure to moisture. As a result, there are no known reports of these mines having caused casualties after the conflict. The mines were ultimately deemed ineffective by the United States military and use was discontinued.[15]



A XM45E1 'Gravel mine'. The cloth casing and explosive charge were designed to be very well protected during storage, and for a very short lifespan once deployed. Image: Fenix Insight Ltd.

In contrast, the United States M19 anti-tank mine incorporates highly resilient materials such as fibreglass and stainless steel, which increase the probability that the casing and fuzing mechanism remain functional, perhaps indefinitely. Most weapons fall somewhere between these two extremes, with compromises in materials and design meaning that certain key components are likely to fail as they are subjected to ageing influences.

A United States M19 anti-tank mine in Jordan. The mine is fully functional and shows few signs of deterioration, despite having been buried for around 40 years. The relatively thick plastic and rubber seals around the threads protect the internal components of the mine. Many M19s cleared in Afghanistan have also been found in good condition. While more susceptible to UV damage if exposed to prolonged sunlight, buried mines with thick plastic casings can be very resilient, possibly as resilient as steel cased ERW in certain circumstances. Image: Fenix Insight Ltd.

The selection of materials outlined above is a deliberate part of the design process, arising from an assessment of need. However, there are also instances where – despite sound assessment - poor design or manufacture renders a munition vulnerable to premature ageing. This may arise for a number of reasons, such as inexperience among the design team, failure to understand the operational environment, inadequate testing or poor quality management during production. An example is where an attempt is made to hermetically seal a casing, but the method fails and water is allowed to enter.

Poor design and production, can make a munition more vulnerable to ageing. The Vietnamese MD-82B has a thermoplastic body, sealed at the top with a rubber O-ring and by melting the side wall to the base. Neither seal is effective, and water frequently enters the casing. The corrosion is partly a result of poor design, failure to understand the operational environment and inadequate quality management. Image: Fenix Insight Ltd.

Good design and production, can make a munition more resilient. The PROM-1 has a sheet steel casing, but this is well protected and the few joints have robust hermetic seals. This is a product of experienced designers with a good understanding of the operational environment, and carefully controlled production. In Bosnia, the PROM-1 has proved the most resilient of the mines laid during the 1990s conflict, and the mine that poses the greatest ongoing hazard. Image: Dutch Defence Expertise Center EOD.

DAMAGE ON DEPLOYMENT

Any damage an item of explosive ordnance suffers on impact will naturally affect how it subsequently ages. For example, an unexploded projectile may strike a hard surface or abrasive medium as it enters the ground; this may destroy the nose structure or fuze and distort or breach the casing. Yet a similar projectile, striking the ground nearby, may sustain very little damage. This introduces a variable that is very unpredictable but can significantly influence the rate at which ageing then occurs.

A BLU-63 submunition that has split apart on impact, exposing the cyclotol explosive fill and aluminium encased M219E1 fuze to the elements. This item will age far quicker than one that was undamaged on impact. Image: Roly Evans

Misuse can yield a similar result. For example, the detonator plug of a landmine may be designed to hermetically seal the casing once it is in place. But if the user accidentally cross-threads the plug, or fails to tighten it sufficiently, it may allow water to enter the casing.

An SB-81 anti-tank mine recovered during clearance operations in the Falkland Islands/Malvinas.

While the mine's glass reinforced polycarbonate casing is extremely resilient, the mine's detonator plug was not properly tightened when the mine was laid.

Examination shows that the loose plug allowed water to enter the casing, saturating the detonator over time.

Images: Fenix Insight Ltd.

MICROCLIMATES

The location where a piece of ordnance lands, or is positioned, is another significant factor in its predisposition to ageing. Shelter from rain and sunlight may be provided by anything from a man-made structure to the leaves of nearby vegetation; this means that similar items of ordnance, perhaps as little as a metre apart, may be subjected to very different influences. In addition to varying degrees of protection from the environment, the exact location of a munition may shorten or extend its exposure to ageing influences. For example, one item may be located near the surface and on a slope, where surface water quickly drains away; another may be in a dip which retains water and therefore keeps the munition wet for prolonged periods. This was observed with landmines in the Falkland Islands/Malvinas, some of which were laid in well-drained areas, with others almost permanently underwater in low-lying bogs. A 2009 ageing study concluded that “multiple landmines recovered from a particular area indicate severe corrosion of the firing pins, and there is evidence of exhaustive interaction with water, it is increasingly likely that most landmines in the area will not function as intended. However, any indicator like this one should always be used with extreme caution; local environmental effects such as a higher, drier area in a field or shielding from rain, could mean that some landmines in any area are still active.”[16]

A Spanish C-3-B anti-tank mine laid in well-drained soil and protected by vegetation.
Image: Fenix Insight Ltd.

A nearby C-3-B mine, which has been submerged in low-lying ground
for more than 30 years. Image: Fenix Insight Ltd.

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CHAPTER 3
FACTORS INVOLVED IN AGEING

The key initial process in the ageing of an item of explosive ordnance is the breaching of the case. How robust a casing is, is therefore a key factor in the resilience of a munition to the ageing process. In addition to this, environmental factors such as temperature, rainfall, exposure to sunlight and soil pH are also highly significant, since these can weaken a casing to the point of breach.

It might be said that there are two distinct stages in the degradation process:

1. effects leading to the breach of the outer casing, and
2. the accelerated degradation of internal components after the ingress of water into the mine or item of ERW.

NATURAL INFLUENCES

For most munitions, the predominant influences leading to the breach of the outer casing are the basic environmental factors of temperature, rainfall and exposure to sunlight. These may be augmented by other factors such as heavily mineralised groundwater or biological activity. All environmental factors may enable or accelerate the ageing process. For example, some soils, may contribute to abrasive effects that remove surface coatings, or plant growth may penetrate cavities and exert mechanical forces that promote breakage. Acidic soils or sediments with a pH of less than 4 in general corrode ferrous metal casings faster than soils with higher pH values.[1] [2] Fire is also a regular natural phenomenon in some regions, and clearly has the potential to effect explosive ordnance. Even animals have been known to dig up, move or gnaw landmines.

Many of these ageing factors can occur simultaneously and may also influence one another.[3] This can make it difficult to isolate the cause and outcome of any given ageing effect, or predict the precise ageing mechanism or time frame with any degree of accuracy.

AGEING INFLUENCES

WATER

Water is probably the single greatest influence on the ageing of ammunition, particularly once it has penetrated the casing and reached internal components. This was recognised in a recent study on landmine ageing, which noted that "the ingress of water is known to be an accelerator of most ageing effects for most mines. Any breach of the outer body of the mine which allows free ingress of water is likely to have significant implications for ageing processes."[4] Similar observations were made throughout the exploitation and ageing studies in the Falkland Islands/ Malvinas, with a 2019 report concluding that "throughout the studies on the ageing of mines, the ingress of water has been established as the greatest single influence on the degradation of internal components. This, in turn, means that the integrity of the casing (its ability to remain waterproof) is important for most mines."[5] This observation is applicable not only to landmines, but also for most types of explosive ordnance.

The rusting of ferrous metals is perhaps the best-known degradation effect of water. This is an oxidation reaction in which iron reacts with water and oxygen to form iron oxide. This can be summarised in the formula: $\mathbf{4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3}$, although rusting actually occurs as a more complex series of reactions. Rust itself has the formula Fe_2O_3, but water is usually present within the compound, to varying degrees. Similar effects occur with other metals, such as aluminium corroding to aluminium oxide. In this case, the reaction is expressed as follows: $\mathbf{2Al + 3H_2O \rightarrow 3H_2 + Al_2O_3}$.

The corrosion of aluminium also results in the evolution of hydrogen gas. This raises yet another variable, which may result in a further chemical reaction, or physical changes, such as the build-up of pressure within a sealed assembly. In studies of aluminium power cables,[6] for example, the build-up of hydrogen from corrosion was found to have led to the damage of the insulating structure. In a munition, this type of affect could also contribute to the failure of a casing.

The presence of compounds dissolved in the water can further affect the degradation. Salt is an obvious and common example of a substance which is known to make water more corrosive, but there are many others. This occurs because, during the oxidation process, metal atoms lose electrons and form ions. When a salt solution (containing ions) is present, it accelerates the process by allowing electrons to move more freely. Ground water frequently contains naturally occurring minerals, such as barium, calcium, sodium and magnesium salts, which can have a similar effect. In many places, wastewater and industrial pollutants are also present.

The effects of salt water versus fresh water are illustrated by examples recovered and examined in the Falkland Islands/Malvinas. A 2019 exploitation report noted that "some of the SB-81 mines analysed and tested during previous phases (in inland areas) were found to be capable of operation, so the poor condition of this sample may be due to their location, closer to the sea, and the more corrosive effect of salt water." [7]

Externally, SB-81 anti-tank mines recovered from coastal areas of the Falkland Islands/Malvinas in 2019 looked similar to those used inland, since there was very little deterioration of the casing. Usually an intact glass reinforced polycarbonate casing would imply functioning internal components. However in this instance some water ingress into the casing has taken place. The presence of salt water in mines from coastal areas has had a significant corrosive effect on the metallic fuze components. The polycarbonate plastic fuze components have proved more resilient. Images: Fenix Insight Ltd.

Dissolved compounds may make the water more conductive, which affects electrical properties through a process known as 'Galvanic Action'. Dissolved compounds also tend to alter the pH of the water, with consequent effects on the type and rate of chemical reaction.

A further characteristic of water is to carry fine solid material, such as sand, that can exert an abrasive effect. This can remove protective surface coatings, increasing the exposure of the casing and leading to more rapid deterioration. Fine solids can also increase the friction between moving parts, which might, for example, prevent the release of a spring-loaded striker. Over a period of years, the build-up of silt within a void may completely block any movement of components within a fuzing mechanism. This was observed in the Falkland Islands/Malvinas in 2019 "where water had washed silt into the mine body, some of the strikers were seized right into their channels and could only be moved using substantial force. Some of the springs below the actuating plunger were also corroded. The presence of sand and salt water adds further ageing influences *compared* to those present inland, with sand having abrasive effects and blocking mechanisms, and salt water being more corrosive." [8]

An Israeli No 4 anti-personnel mine in the Falkland Islands/Malvinas, recovered from a coastal minefield near Port Stanley in 2019. Water often carries fine particles, such as sand, which have an abrasive effect and can fill voids within the fuze mechanism, blocking its action. The No.9 fuze igniter seen here is heavily corroded and no longer functional although it still presents an explosive hazard. Image: Fenix Insight Ltd.

Similar types of ammunition may age at very different rates, depending on whether they are located in a wet or dry environment. A stark illustration of this can be seen with mines of similar production dates and time in the ground. During studies undertaken in the early 2000s, buried PMN mines in Cambodia (a tropical country subject to heavy rainfall) were mostly non-functional, whereas similar mines in dry areas of Afghanistan were often still functional despite being laid in the 1980s.

Left: A PMN mine recovered in Cambodia. The hot wet climate has caused the rubber cover to perish and the securing band to rust through. Right: A PMN of a similar age in Afghanistan has been well-preserved, with little deterioration of the rubber cover or securing band. Images: Fenix Insight Ltd.

GALVANIC CELLS

Another ageing mechanism involving water is the formation of galvanic cells. This is an electrical phenomenon, which results in the components of a munition behaving like a battery. Mineralised water acts like the electrolyte, without which the battery could not function. “Galvanic cells play an important role in the degradation of the inner metal workings of the landmine by corroding them. These cells work by having several metals and salts in an aqueous solution. This causes a potential difference to be formed, then reduction and oxidation takes place.”[9]

The more dissimilar the metals (in terms of their reactivity or electronegativity), the greater the galvanic effect and the more reduction and oxidation that takes place. This reduction and oxidation is effectively ‘corrosion’ and causes many of the changes that contribute to the ageing process. “A difference in electrical potential exists between the different metals and serves as the driving force for electrical current flow through the corrodant or electrolyte. This current results in corrosion of one of the metals.“[10]

SOIL

Most soils are comprised of a complex mixture of minerals, often with a significant water content. Therefore they incorporate a range of characteristics that may affect the ageing of explosive ordnance. In 2008 the Material Science Faculty of James Madison University summarised the characteristics of soil that affect the ageing of explosive ordnance as follows:[11]

Moisture content. The moisture content of a soil is often an enabler of other ageing factors or mechanisms, such as carrying minerals in solution or silt particles in suspension.

Minerals and elements. The texture and structure of soil affects how it abrades explosive ordnance, with cohesive soils (containing a high percentage of clay) being much less erosive than sandy soils. Soils with a high organic carbon content, such as swamps, peat, fens, or marshes, as well as soils that are severely polluted with fuel ash, slag coal, or wastewater, tend to be highly corrosive.

pH. The pH level also affects soil corrosivity. Normal soils with pH levels between 5 and 8 do not contribute to corrosivity. In fact, soils with pH above 5 may form a calcium carbonate coating on buried metals, protecting them from extensive corrosion. However, highly acidic soils, such as those with a pH below 4, tend to be highly corrosive. Acidic conditions promote corrosion of metals and other materials such as rubber.

Buffering capacity. Buffering capacity is a measure of the soil's ability to withstand extreme changes in pH levels, and also affects its corrosion potential. Soils with a high buffering capacity can maintain pH levels even under changing conditions, thereby potentially inhibiting corrosive conditions. However, soils with a low buffering capacity that are subject to acid rain or industrial pollutants may drop in pH levels and promote corrosivity.

Resistivity. Resistivity, or electrical conductivity, is dependent on moisture content and is produced by the action of soil moisture on minerals. At high resistivity levels (greater than 20,000 ohm/cm) there is no significant impact on corrosion; however, corrosion can be extreme at very low resistivity levels (below 1,000 ohm/cm).

Electrochemical (redox) potential. The electrochemical or "redox" potential is the ability of the soil to reduce or oxidise (metal) casings (the oxidation-reduction potential). High electrochemical potential can contribute significantly to corrosion.

Oxygen. The presence of air, containing oxygen, is a prerequisite for corrosion such as rusting. Even when water is present, rusting will not occur without oxygen. Aerated soils contain the necessary oxygen to oxidise metals but some, such as heavy clay, may exclude oxygen quite efficiently. This is why heavy ordnance, such as bombs and projectiles, that have penetrated deep into clay may be found well-preserved many years later.

The nature of the soil can also affect the fate and transport of energetic materials that can leach once the casing of explosive ordnance is breached. Acidic soil is likely to enable greater transportation of contaminants, enabling potential contact with water sources.[12] Small arms ammunition is also particularly prone to corrosion in such conditions since "lead corrodes and leaches readily in acidic conditions to concentrations that can exceed guidelines for human health and con-trolled waters."[13]

Heavy clay may exclude oxygen and thereby almost prevent the corrosion of ferrous metals. This Mk82 aerial bomb was found in clay soils in Phnom Penh in 2015. Image: Len Austin.

MICROBIAL ACTIVITY

Almost all soils contain microorganisms or 'microbes', which range from microscopic bacteria and unicellular (single-cell) organisms, to the larger multicellular creatures and plant forms (including fungi).[14] These microbes can cause chemical changes in natural environments, much as they do in fermentation processes, such as the production of bread, cheese and alcohol. In many cases, the product of microbial activity is acidic, leading to conditions that promote the corrosion of metals. Microbial activity within recovered soil samples can be established by examining the carbon and nitrogen content. This carbon to nitrogen ration (C:N ratio) acts as an index of microbial activity, with a high proportion of nitrogen indicating correspondingly high microbial activity. While microbial activity undoubtedly has the capability to influence ageing, it can be difficult to directly associate the cause and effect. After examination of certain simple mine types (Russian PMN and PMD-6) in different soils, one study noted that "although it might be tempting to attribute differences in soil C:N to patterns of landmine aging, a closer inspection of the same landmines, determined in the field to either be likely to function or unlikely to function as intended, does not reveal any systematic pattern. Both functional and non-functional PMN landmines had relatively high C:N, implying potential nitrogen limitation of soil decomposition processes. Conversely, all PMD-6 landmines were deemed not functional and yet showed the greatest range in C:N."[15] This does not mean that the effect of microbial activity is insignificant, it merely reinforces that fact that many influences are at work simultaneously, and that it is sometimes very difficult to precisely attribute the various aspects of ageing to individual factors.

VEGETATION

Closely associated with soil is the vegetation that is often present within it. Plants can exert a variety of effects ranging from beneficial to destructive. The shelter provided by leaves near ground level, or a higher canopy, may protect ordnance from rain and sun, significantly reducing the harmful effects from both. However, root structures may enter the smallest cracks and crevices, penetrating munitions and – with weak or thin-cased items – even levering them apart. Where roots penetrate a munition casing, the often provide a means for water to enter. In this sense, they can become an accelerator of ageing.

A Russian PMN-2 anti-personnel mine recovered from northern Cambodia in 2009. Small roots have spread into the small gaps and joins around the pressure plate. Disassembly of the PMN-2 mine shows that the root structure has penetrated the mine casing, levering components apart and allowing water to enter.
Images: Fenix Insight Ltd.

In some instances, root structures or plant growth may surround or engulf munitions, protecting them from other sources of mechanical damage, but also preventing access for deminers and EOD personnel.

SUNLIGHT

Sunlight, and in particular the ultra-violet (UV) spectrum, is known to cause degradation of materials such as plastics. "UV radiation causes photo-oxidative degradation which results in breaking of the polymer chains, produces free radical and reduces the molecular weight, causing deterioration of mechanical properties and leading to useless materials, after an unpredictable time."[16] In simple terms, many polymers (such as plastics and rubbers) tend to become more brittle with prolonged exposure to UV light.

A C-3-B anti-vehicle mine found in the Falkland Islands/Malvinas in May 2018. The mine has been on or near the surface for approximately 36 years and shows case cracks consistent with damage from UV light. Image: Guy Marot.

A Russian PMN anti-personnel mine recovered in Afghanistan in 2010. This mine was left on the surface and suffered prolonged exposure to sunlight. The rubber has lost its flexibility and become extremely brittle, resulting in the formation of cracks and loss of some sections. This has breached the integrity of the casing and allowed water to enter the mine, causing corrosion damage to the internal mechanical mechanism, particularly the spring that supports the last holding device in the mine but also the coiled spring that is part of the striker assembly. The bakelite body of the mine is remarkably resilient however. Image: Fenix Insight Ltd.

Another aspect of ageing is the change in appearance of the item. Although this may have little consequence for functionality, a change in appearance can be particularly significant for recognition. Soldiers, deminers, aid workers, and affected populations are often shown images or examples of dangerous items, so that they can recognise, avoid and report them. In many cases, what they are shown represents the munition in pristine condition, whereas what they are likely to encounter may have a very different appearance because of ageing. In some cases, this may make it unrecognisable.

A composite image contrasting the appearance of a new Chinese Type 72 anti-personnel mine (to the left) with its appearance after years of exposure to sunlight in Cambodia. The green cover is made from thin rubber, which becomes grey and perishes, exposing the buff-coloured pressure plate beneath. The result is that the aged mine looks nothing like it did when new, making it difficult to recognise.
Image: Fenix Insight Ltd.

FIRE

Brush fires are a regular natural phenomenon in many parts of the world, and regularly sweep through dry surface vegetation. In many cases, the effect is relatively superficial and may pass relatively quickly – perhaps in a matter of minutes. This is often the case where fires occur regularly, so that dry vegetation never gets a chance to accumulate.

Thin cased ordnance, such as blast landmines, on or near the surface may begin to burn, and once the main filling ignites, the combustion usually proceeds to complete destruction. The burning explosive is consumed quite steadily until the flame front approaches the detonator, at which point there is an explosion that often detonates any remaining high explosive. Just as hardy shrubs and trees often survive these fires, resilient or thick-cased ordnance may also be relatively unaffected. Similarly, mines and other ordnance buried more than a few centimetres are likely to be unscathed, in the same way that root structures and subterranean creatures tend to survive.

“In order to help understand effects of fire, it is necessary to determine the depth that heat can travel in various soils. There appear to be three primary factors that determine the overall temperature depth penetration in soil. First, water content of the soil: if the soil can retain a large amount of water or it has recently rained, then it is less likely that the fire will be able to heat out the soil as dramatically as if it were dry. Second, the intensity of the fire, or how hot the fire is. The temperature goes through an exponential decay as it propagates through the soil, therefore requiring a more intense fire to generate a higher temperature gradient through the soil. Third, how long the fire is in a given area.” [17]

Even relatively brief events, causing superficial damage, may have a significant effect on ageing. One way this can occur is by damaging or removing a protective coating, such as rust-resistant paint. This may then expose the surface prematurely, allowing more rapid corrosion. Plastic components may melt, and rubber seals may also be damaged, allowing water to enter a previously sealed casing.

Russian S-24B rockets in a depot in Mozambique in 2014. At some point, fire has swept through the vegetation, burning the paint from the upper surfaces but failing to initiate the motors, also leaving the paint on the underside relatively unscathed. Where the paint has been removed, the exposed metal has rusted.
Image: Fenix Insight Ltd.

"Depth and intensity of heat penetration (particularly a result of fires) in various soil conditions leads to different physical and chemical changes. Metals will have little to no physical change while plastics go through a range of reactions depending on plastic type and temperature, from soft and disfigured to rigid and crumbly change. Significantly, some polymers may undergo a vulcanization effect with heat, leading to greater resilience against physical and chemical degradation." [18]

Russian PMN-2 anti-personnel mines recovered from different minefields in northern Cambodia in 2009. The mine in the foreground has been severely damaged by fire, which has burned away the cruciform pressure plate and allowed water to enter the mine. The explosive components are undamaged but, ironically, the loss of the pressure plate means that this mine could no longer function as designed.
Image: Fenix Insight Ltd.

Intense heat may also accelerate the degradation of internal materials, including explosive fillings, long before they catch fire or explode. Many explosives swell and generate gases as they become hot, which may cause enough internal pressure to distort the casing. In addition to these physical changes, the products of degradation may be prone to chemical interaction.

A Belgian M35 anti-personnel mine in Jordan, 2010, where a brush fire has swept through the minefield. The majority of the mine was buried, so reasonably well protected, but the fuze was burned and is no longer waterproof. The TNT explosive filling in the lower body of the mine has swelled, bulging the normally flat top surface and discolouring the plastic. As the body cooled, it remained in this position, so that the new shape and colour make the mine difficult to recognise.
Image: Fenix Insight Ltd.

In thick-cased munitions, such as bombs, mortar bombs and projectiles, hot fillings may melt and expand to the point where they breach internal seals and are forced out of the munition. This is known as 'exudation' and happens most often with white phosphorus (WP), which is used in incendiary and smoke ammunition. WP melts at around 45°Celcius, which is easily reached as a ground temperature in hot countries. The high temperatures often result in seals hardening and cracking, making exudation more likely. If the filling does escape from the munition, it is likely to spontaneously combust on contact with air; this is believed to be a cause of fires starting in ammunition stockpiles.

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CHAPTER 4
CHANGES DUE TO AGEING

The eventual effect of most ageing is that ammunition will cease to function as designed. The time scale may be protracted and unpredictable, and the degradation process may involve a number of stages. There may be a phase during which ageing changes actually make the munition more dangerous than when it was fired, dropped or emplaced, through sensitisation of the in-built fuzing mechanism. This is often a concern for EOD operators. Gradually, most ammunition experiences multiple points of failure, which usually means that the likelihood of accidental initiation continues to decrease. Nevertheless this can take many decades, possibly more than a century. TNT explosive from World War I projectiles, for example, is still capable of detonation.

The stages of ageing can be likened to the ageing of a car, which is designed with a useful life of, say, 10 – 20 years, but may endure much longer if sheltered and well-maintained. Even when abandoned, the interior of the car remains in good condition until a window is broken, seals fail or the roof rusts through. Once exposed to the environment – and particularly to water – the interior fittings and mechanisms begin to degrade quickly. The car may simply become incapable of driving, or there may be a stage where it becomes more dangerous; perhaps the engine runs, but the brakes or steering don't work. At some stage, it becomes incapable of moving and, eventually, the fuel evaporates or drains out and the battery loses all charge.

Abandoned projectiles in Iraq. Whether ERW is fuzed or armed, it remains an explosive hazard. Image: Roly Evans.

FAILURE MECHANISMS

Changes due to ageing, which lead to the inability of the ammunition to function as designed, normally involve one or more of the following:

- Failure of the casing
- Failure of the fuzing mechanism
- Failure of the explosive train.

In many cases, it is degradation of the casing that accelerates the changes in the fuzing mechanism and explosive train. This is because the casing usually provides a high degree of protection until it is breached but, once this has occurred, the internal components often become exposed to water and other ageing influences.

This means that the accelerated internal degradation begins as soon as the integrity of the casing is breached, whether that is through the side wall of the munition, a screw-in fuze or plug, or a sealing ring or washer between sections or components. Once this breach occurs, the degradation of key internal components proceeds at different rates, dependent on their individual vulnerabilities and the influences to which they are exposed. The subsequent failure of any one key component may render the munition incapable of functioning as designed; this is illustrated in the figure below.

It is important to emphasise that the inability to function *as designed* does not mean the munition cannot function in some form and does not necessarily make the munition 'safe'. This is because:

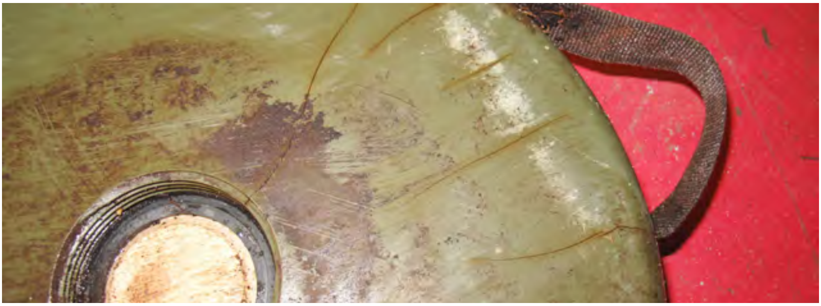
- It may be capable of functioning despite the failure of a key component
- Incomplete function (such as the explosion of the detonator alone) may still be possible
- Initiation may result from a substantial energy input (such as fire or impact)
- An alternate and unintended initiation mechanism may form as a result of ageing.

FAILURE OF THE CASING

LIGHTWEIGHT CASINGS

Casing failure is most likely to occur with lightweight, thin-cased munitions, such as blast landmines, rockets and missiles. Most of the materials commonly used for ammunition casings are vulnerable to ageing influences. At the beginning of case failure, water and other external influences may begin to penetrate the munition, leading to the degradation of internal components. This is particularly noticeable with landmines, such as the Russian PMN and Chinese Type 72, which use thin rubber membranes to seal the upper surface.[1] More serious failure of a casing may affect the structural integrity of the whole munition. This can lead to sections or components separating from one another, including the loss of the explosive filling.

Thin rubber is certain to perish after decades of exposure to an outdoor environment. Mines such as this Chinese Type 72 change appearance significantly when the rubber covers degrades, also exposing internal components to ageing influences and accelerating the ageing process. The safety pin is still in place with this abandoned mine. The mine has not been armed. Image: George Zahaczewsky.



Cracks in the casing of a recovered Spanish C-3-B anti-tank mine in the Falkland Islands/Malvinas, 2013. These were probably caused by a combination of the plastic becoming brittle, and the repeated expansion and contraction (diurnal cycling) of the explosive filling over more than 30 years. Cracks like this were found in many of these mines. Image: Fenix Insight Ltd.

In many weapons, the casing provides momentary confinement during initiation, holding the explosive filling in place as the detonation wave progresses through it. Without this effect, detonation may be incomplete, with the warhead blowing itself apart before the explosive can be fully consumed. Thin metal plate casings may corrode away relatively quickly, especially if other conditions (such as abrasion of coatings) predispose them to ageing. This may apply to a complete casing, such as the body of a landmine, or one component or section of a casing, such as the windshield on a projectile or fuze.

Russian 30mm cannon ammunition in Afghanistan, 2020. Some of the A-670M fuzes have lost their windshields, allowing water to penetrate the fuze body.
Image: The HALO Trust.

Although the rusting of ferrous metals is probably the best-known metallic corrosion, most thin metals are vulnerable to degradation. This includes aluminium alloys, copper, zinc and even stable alloys such as brass, any of which can react with minerals, or undergo galvanic reactions that weaken or destroy them. Some of the thinnest metallic casings are used to encapsulate igniters and detonators. Once that protection is removed, these sensitive components can be left vulnerable to impact, damage or chemical reaction.

A Russian MUV-2 fuze from a PMD-6 anti-personnel mine recovered in Cambodia, 2010. The upper hollow section of the aluminium detonator capsule has corroded away, separating the explosive from the fuze. Since the mine was buried, this gap was then filled with earth and probably would have prevented the fuze from functioning. Image: Fenix Insight Ltd.

HEAVY CASINGS

Heavier ammunition, such as mortars, projectiles and air-delivered bombs, tends to use steel alloy casings, which are designed to resist the enormous forces involved in firing, flight and impact. In most instances, the casing itself remains intact, but weaknesses are often present where separate components meet, at joints, plugs and seals. External assemblies, such as fuzes, are usually far more vulnerable than the main body, so if they are heavily damaged or destroyed on impact (as they often are) they provide a breach into the casing. Even in stockpiled or abandoned ammunition, joints or screw threads between assemblies are the weak spots.

Weathered AXO gathered by local farmers. Note that corrosion of the fuzes is more advanced than on the mortar bodies. Image: Roly Evans.

Nose sections of United States Mk 82 bombs dropped during the Indochina Wars and recovered, unexploded, in the early 2000s. These heavy steel casings were virtually unaffected by impact, other than the loss of paint coatings. Both have been exposed to water for nearly 50 years, but have corroded differently, possibly because of the soil conditions in which they were buried. The nose fuzes were heavily damaged on impact, but even the heaviest corrosion would still take several more decades to penetrate the steel casing. Image: Fenix Insight Ltd.

Externally, this Vietnam-era US M107 155mm HE projectile, recovered in 2018, appears heavily rusted. However, once cut open to reveal the HE filling, the thickness of unaffected steel becomes apparent. This is typical of many steel-cased munitions, such as mortar rounds, projectiles and air-dropped bombs. Image: Fenix Insight Ltd.

An x-ray image of a German GrZ04 fuze in a remarkable condition, with springs still intact. Many World War I artillery projectiles had fuzes that were largely internal to the fuze pocket and have therefore been protected by the thick steel casing. What is not visible is any ageing of the pyrotechnic holding devices within the fuze that often degrade due to humidity. Image: Belgian EOD Group (DOVO-SEDEE).

FAILURE OF THE FUZING MECHANISM

Fuzes are critical to the function of ammunition, being responsible for initiation at the right time and place to fulfil the weapon's role. In order to achieve these demands, fuzes often incorporate a combination of systems including some, or all of the following:

- Mechanisms, including strikers, springs, rotors, slides, detents and escapements, and sometimes clockwork.
- Electrical systems, including wiring, switches, electronic components, batteries, and sometimes generators.
- Pyrotechnic components, such as electrical squibs, mechanically-initiated igniters and powder-train delays.
- HE components, such as detonators, relays and boosters.

In addition to the system designed to cause initiation, many fuzes incorporate systems with other functions, such as:

- Safety and arming
- Delay (to initiation)
- Self-destruct back-up
- Optional settings (such as impact or delay, and variable delay).

All of components necessary to achieve these functions must be packaged into an assembly appropriate to the size of the munition. This means that many of the components are miniaturised as far as possible, making them inherently vulnerable. The fuze casing is usually made as light as possible, often from aluminium alloy.

Fuzes come in a vast range of sizes, shapes, materials and complexities, so it is difficult to make definitive statements about the effects of ageing; however, the following findings from previous studies highlight typical issues.

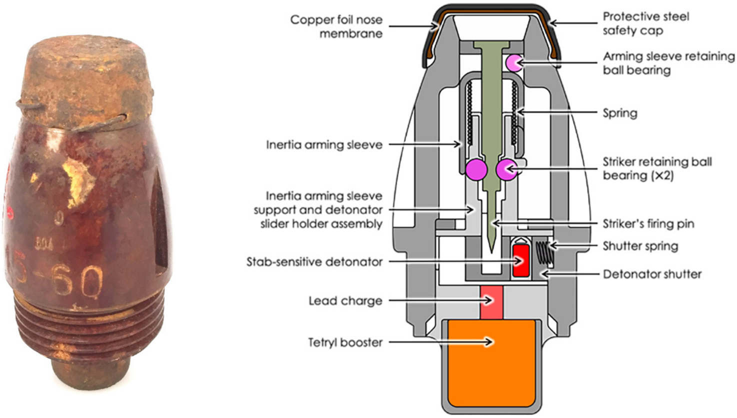
POINTS OF FAILURE

The actuation of a fuze involves a series of steps or processes, most of which are critical to achieve initiation. The example below shows a simple fuze, along with the process that occurs during actuation. This process is linear and sequential, meaning that anything that prevents a step - or the transition between them - from occurring is likely to halt the chain of events and prevent initiation.

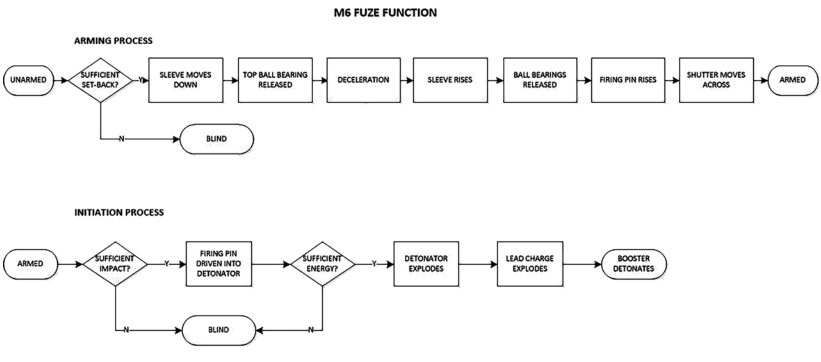
Interference with the process, due to ageing, might include:

- Increased friction between components preventing movement due to surface corrosion
- Decreased spring power due to metal degradation
- Insufficient strength of detonation within the explosive train.

Any one of these could halt the initiation sequence and prevent the fuze from operating as designed. This includes its operation during its intended use; this would mean that – when fired – the mortar may fail to detonate on impact and become an item of UXO. Or, if stockpiled or abandoned (AXO), it may mean that the fuze becomes less prone to accidental initiation through handling, tampering or other accidental actuation. An item of EO that has been fired or emplaced and armed will be invariably in a more hazardous state than an item which has simply been stored or abandoned. The difficulty facing the EOD operator is that it is often difficult to determine why an item failed to function in its designed mode.



The Russian M-6 is a relatively simple mortar fuze, which incorporates an arming and impact initiation mechanism. Image left: Dutch Defence Expertise Center EOD. Image right: Fenix Insight Ltd.

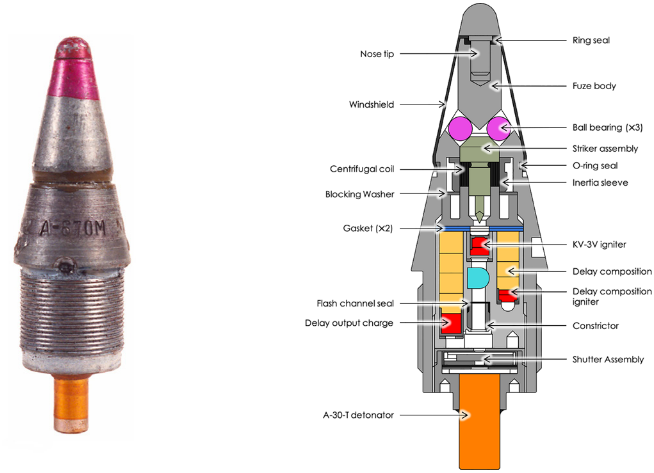


Even a simple fuze, such as the M-6, involves a number of steps within its arming and actuation process. A failure of any step, or interference between them, is likely to result in the fuze failing to function, and the main charge remaining unexploded.

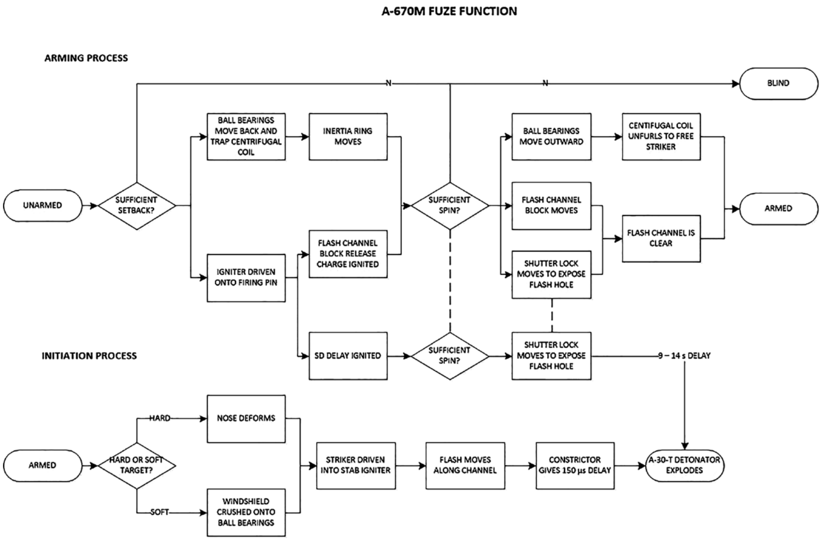
The same influences and effects apply to more complex fuzes, but there may be additional steps within the initiation sequence, meaning that there is potentially more to go wrong; in other words, there may be a large number of points at which the fuze can fail. Many complex fuzes incorporate parallel paths, meaning that a break in one sequence does not necessarily halt the initiation process. In other words, a parallel path may allow actuation to bypass a point of failure.

The Russian A-670M is a small fuze used in 30mm cannon ammunition. It incorporates an arming and impact initiation mechanism, but also a self-destruct feature, designed to detonate the warhead after a short delay if the projectile does not strike a target. The ability of a single failure point to prevent initiation depends on whether that failure occurs within a single or a parallel sequence. For example, 'setback', the force of inertia experienced on firing, is required to both arm the impact initiation mechanism and to ignite the self-destruct delay. If there is insufficient setback, then neither of these sequences can proceed. However, once the fuze has experienced sufficient set-back, a failure in the impact initiation mechanism will not prevent the self-destruct from operating, or vice versa.

This is important because many fuzes rely on the same single arming action (such as setback, spin rate, electrical pulse or pyrotechnic delay) to begin parallel actuation mechanisms. So, the failure of an early step in the sequence often prevents the operation of systems which are meant to provide redundancy; this is why many weapons, such as submunitions, are found unexploded, despite incorporating 'back-up' self-destruct devices.



The Russian A-670M is a fuze used in cannon ammunition and incorporates a self-destruct system in addition to an arming and impact initiation mechanism. Despite this complexity, the entire fuze is only 67mm long and 26mm in diameter, meaning that the internal components are very small. Image on left: United States Department of Defense. Image on right: Fenix Insight Ltd.



The processes of arming and initiation within the Russian A-670M cannon ammunition fuze. The sequences involve a number of parallel processes, which provide opportunities for initiation to bypass a point of failure.

MECHANICAL FAILURE

Mechanical failure typically occurs when the energy input of a step in the initiation sequence is insufficient to actuate the next step, due to the effects of ageing. In mechanisms, this is often due to an increase in friction, which impedes, or prevents, the movement of critical components.

Examples are often seen within the many types of fuzes that incorporate spring-loaded strikers to fire igniters. The spring (often made from ‘music wire’ with a very high iron content) tends to rust through, collapse or become corroded into place. Since rust occupies more volume than the original iron, it often fills the gaps that are needed for correct function. Most fuzes have fine tolerances between components, so that even small dimensional changes can prevent their operation.

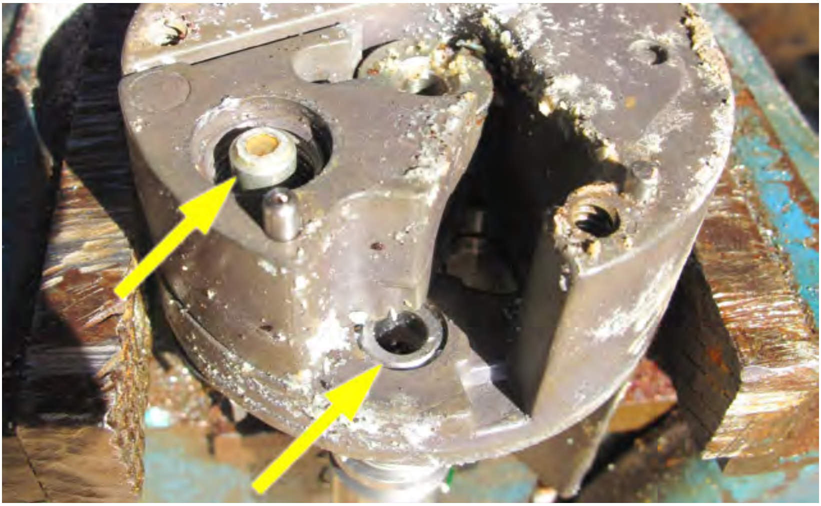
The striker and spring from a Russian PMN mine recovered in Cambodia, 2014, with an example of the spring in good condition, above. The corroded spring has lost its ability to drive the striker into the detonator assembly; in other words, it can no longer supply the energy needed to allow the initiation sequence to reach the next stage. This will prevent the mine from functioning as designed and is typical of many such applications within fuzes. Image: Fenix Insight Ltd.

The springs in this Russian PMN-2, also recovered from Cambodia in 2014, are in good condition; however, the plating on the striker has been lifted and bulged by corrosion (yellow arrow). Because of the fine tolerances in the fuze, this small dimensional change is sufficient to seize the striker into place and prevent the mine from operating. Image: Fenix Insight Ltd.

Springs are often used for other functions, such as the alignment of components within the firing train; here they turn rotors or push slides (containing the detonator) into line with firing pins and strikers during the arming process. Once again, the inability to arm will prevent the munition from functioning as designed.

This fuze is from the Russian PTAB-2.5M submunition, which is found within the stockpiles of many countries. In this example, the small spring (yellow arrow) that turns the detonator rotor has failed due to corrosion. This spring is responsible for bringing the detonator into line with a booster and making an electrical connection. This tiny component is the only point of failure in the whole munition, but it is enough to prevent it from operating. Image: Fenix Insight Ltd.

Since ageing usually involves corrosion, and other effects that lead to an increase in friction, components in old munitions become progressively less likely to move. This means that the chances of an unarmed munition becoming armed lessen, and vice versa. In AXO fuzes should not be armed, so the effects of ageing are normally to decrease the likelihood of them accidentally becoming armed. In UXO that failed to detonate because their fuzes did not arm correctly, ageing is likely to preserve them in the arming state they reached on impact. If a fuze is fully armed, then ageing is likely to preserve this condition.



An FMU-54B bomb fuze recovered from a United States bomb dropped during the Indochina Wars. The yellow arrows indicate components of the initiation train that are out-of-line because the rotor did not move across: this is probably why the bomb failed to explode. The corrosion and friction resulting from ageing is likely to prevent this rotor from moving, preserving the fuze in its unarmed condition. Image: Fenix Insight Ltd.

With mechanical fuzes for mortar bombs, projectiles, submunitions, rockets, missiles and air-dropped bombs, arming is usually an irreversible process. However, victim-actuated munitions such as mines, booby traps and some demolition devices, may be designed so that they can be neutralised[2] or disarmed[3]. In some instances the effects of ageing may inhibit the potential to neutralize or disarm an item. This can make a Render Safe Procedure (RSP) difficult to achieve.

A United States M15 anti-tank mine, encountered in 2010 in a minefield on the Jordanian border with Syria. Disarming this mine should be a simple matter of unscrewing the central plug and removing the fuze; however, the plug is firmly rusted into place. This is an example of ageing preventing a render-safe procedure, leaving demolition as the only practical disposal option. Image: Fenix Insight Ltd.

The shape and structure of critical components such as firing pins can change so much that they can no longer fulfil their function. The firing pins used to initiate stab-sensitive igniters are particularly vulnerable, since they must be both sharp and long enough to penetrate the igniter. When corrosion takes hold, the profile of a sharp pin frequently alters as the thinnest section, the point, recedes. This both shortens and blunts the pin, eventually rendering it incapable of initiating the friction-sensitive composition.

Firing pins recovered from United States M14 anti-personnel mines in Jordan during the early 2000s. The pin on the left is virtually as-new, but the pins in the centre and right have become shorter and blunter. These are unlikely to initiate the mine's stab-sensitive detonator. Corroded firing pins will also make the mine even harder to detect. Images: Fenix Insight Ltd.

TRIPWIRES

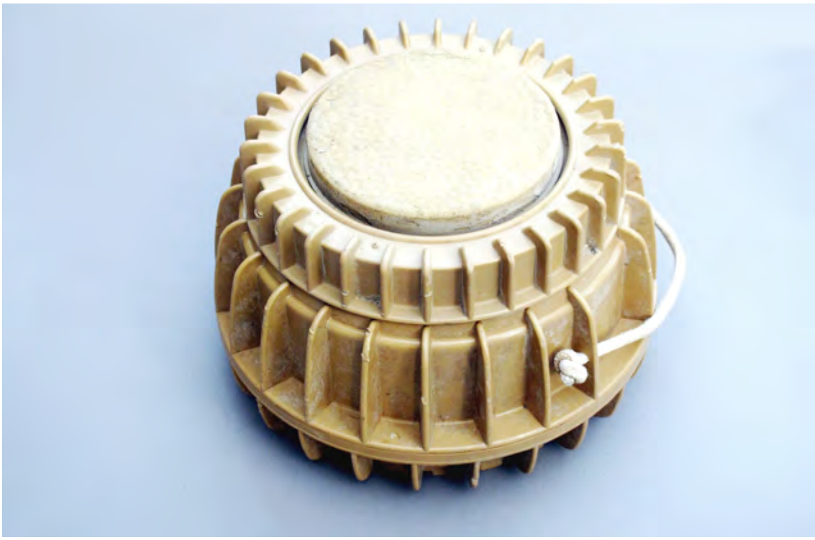
Tripwires are often used to initiate fragmentation mines, so that their lethal range can be used to best effect. Most tripwires are made from iron or steel wire, often with only a thin layer of protective paint or surface coating. The wires themselves are usually less than 1mm in diameter and extend over several metres, meaning that they have a very large surface area in proportion to their mass and making them very vulnerable to corrosion.

In many of the world's minefields, tripwire-actuated mines were laid more than 40 years ago. In wet climates, these wires have mostly rusted away completely so that, even if the fuze were operational, it now has no means of actuation. "Most tripwire is made from mild steel and, given the degree of corrosion observed on exposed steel surfaces (such as the bands on PMN mines), it is virtually inconceivable that a complete tripwire of the same age, several meters in length, could have survived intact."[4] How tripwires used in the conflict in Ukraine age will be an interesting area of research. Metal tripwires are known to be a receding hazard to deminers in Cambodia. This had important implications for the tools and techniques used during demining; for example, brush cutters can be used to clear vegetation without the concern that they might initiate tripwire-activated mines. Use of fishing line as tripwire is also known. Whether such wire remains intact longer than the fragmentation mine it is employed to initiate is unknown and an area for further research.

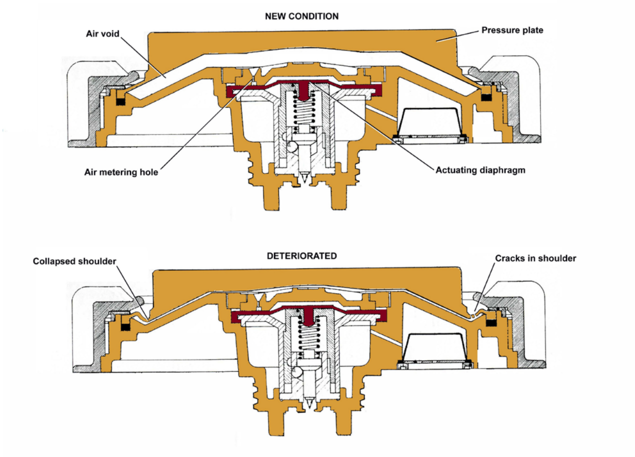
Contrary to popular belief, most tripwires are made from iron or steel, with little or no protection. Tripwires used with mines like this Chinese Type 59, laid in Cambodia more than 40 years ago, rusted away many years ago. Image: Fenix Insight Ltd.

TRANSMISSION MEDIA

In addition to tripwires, some fuzes use hydraulic and pneumatic systems in which liquid or air are used to transfer movement (such as the actuation pressure) from one component to another. This is similar to the use of a hydraulic braking system in a car, where pressure on the brake pedal forces fluid from the master cylinder, down a tube, to a slave cylinder, where it is used to move a brake pad. Hydraulic systems are used in the fuzes of several mines,[5] as well as self-destruct devices, while pneumatic systems feature in the shock-resistant fuzes of virtually all modern Italian mines, and their many copies. Without the confinement of the transmission media (liquid or air) the system cannot operate as designed. Thus, much like a broken brake line on a car leading to brake failure, any breach of the system that leads to leakage is likely to prevent the operation of a fuzing system. TC/6 mines in Afghanistan were known to often have cavities that had been breached.



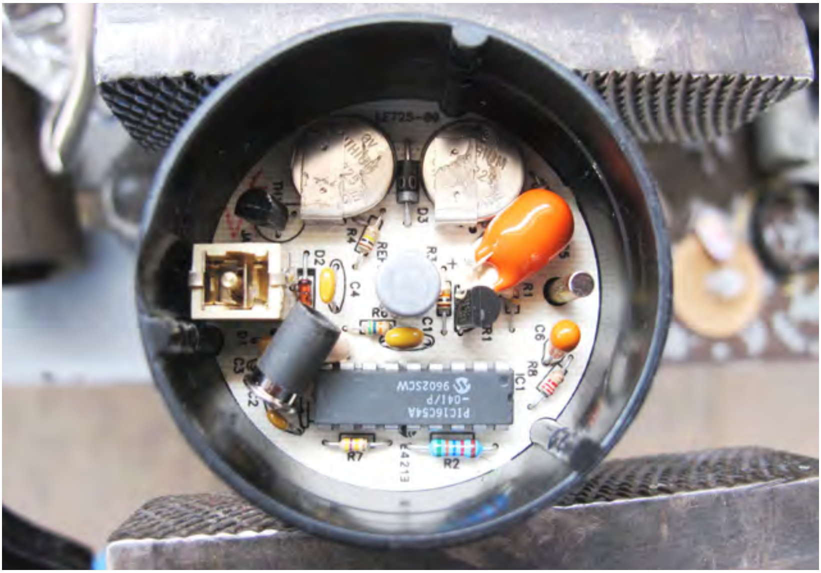
The Italian TC/6 anti-tank mine is one of many designs that use a pneumatic transfer system. When mines are exposed to heat or sunlight for prolonged periods, the elastomer pressure plate becomes brittle, causing the seal around the shoulder to fail. Once air is allowed to escape from beneath the pressure plate, the pneumatic actuation system can no longer operate. Image: Fenix Insight Ltd.



Top: The air-filled cavity beneath the pressure plate prior to the application of pressure functioning the mine. When pressure is applied, this air is used to distort a diaphragm and actuate the fuzing mechanism.
Below: When the cavity is no longer air-tight, no pressure can be generated and the pneumatic actuation system becomes incapable of operation. Image: Fenix Insight Ltd.

ELECTRICAL FAILURE

Most electrical fuzes use batteries to supply their power, but the way in which that electrical energy is stored and supplied can vary significantly. In modern military applications, lithium batteries may be used because of their long life and reliability. When disconnected or isolated from a circuit, lithium batteries manufactured to high specifications (such as 'military-grade' batteries) are typically expected to last for at least 10 years[6], although research shows that they can last considerably longer. This lifespan is a function of the battery's steady deterioration, even under ideal conditions, but in an adverse environment, that lifespan can be reduced significantly. "Over their lifespan batteries degrade gradually leading to reduced capacity due to a variety of chemical and mechanical changes to the electrodes. Some of the most prominent mechanisms include the growth of resistive layers (solid electrolyte interphase, or SEI) on the electrode surfaces, lithium plating, mechanical cracking of the SEI layer or electrode particles, and thermal decomposition of electrolyte."[7]



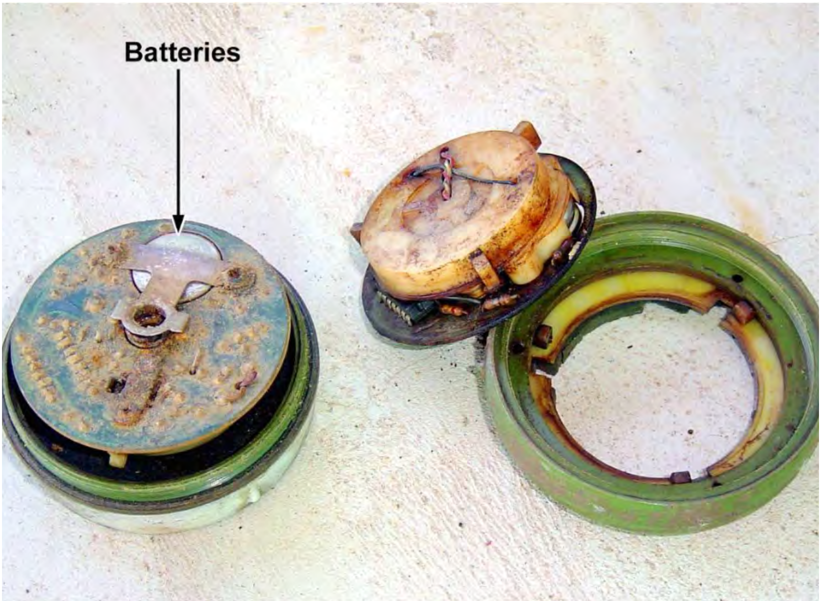
The electronic fuze of a Spanish SNA submunition is powered by two lithium batteries. These batteries are isolated from the circuit until the weapon is deployed. Image: Fenix Insight Ltd.

The batteries were manufactured in 1996. Testing showed that the batteries still retained full charge, around 25 years after they were manufactured. Image: Fenix Insight Ltd.

If the batteries are connected into an active circuit, where they power a 'load' (such as a sensor), the constant drain means that the lifespan is likely to be considerably shorter – perhaps somewhere between a week and a few months.[8] In between the 'disconnected' and 'active load' instances are applications where an electrical circuit is live, but little or no current flows until the actuation input triggers the fuze. A simple every-day example is a torch, where the battery power is always available, but only used when the switch is closed. In these applications, battery life may approach 'disconnected' levels of many years. It is for this reason that IEDs that are armed or initiated by some form of radio frequency will invariably drain batteries quicker than simple victim operated mechanical circuits.

A further complication is that many firing circuits use capacitors to store charge, which is released to initiate a squib or detonator during fuze actuation. Capacitors gradually leak charge, so the need for the battery to constantly 'top-up' that charge means that they run down faster than they would if isolated. However, in some cases, the capacitors may retain enough charge to fire the device when the batteries are flat, or even when they are absent.

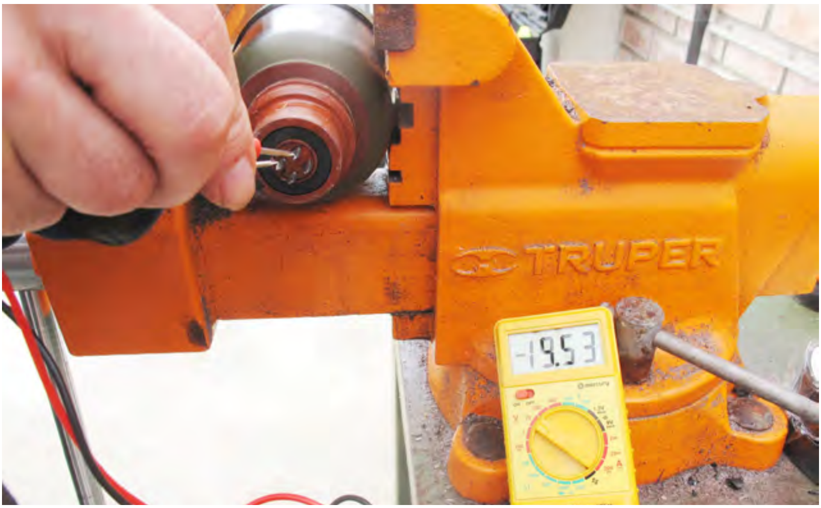
An FMU 139 A/B electro-mechanical fuze in the tail of a MK-83 aircraft bomb in Iraq. The fuze contains capacitors charged from the employing aircraft prior to being dropped. The charge has long since dissipated. Image: Roly Evans.



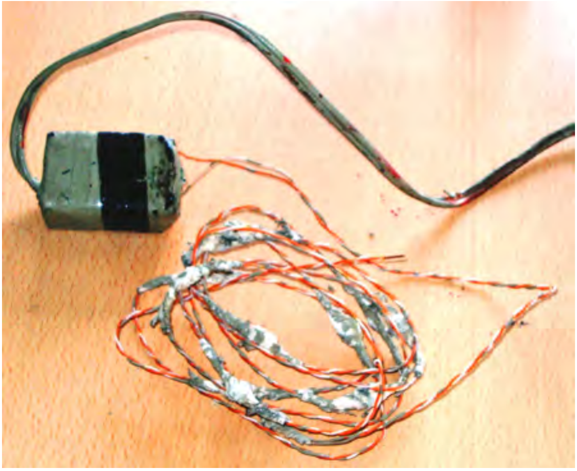
Lithium batteries in a Chinese Type 72B mine recovered in Cambodia were found to be discharged below the firing threshold, 30 years after the mine was laid. "The Type 72B is an electronic anti-disturbance/anti-handling variant of the Type 72. Although externally identical once armed, this mine contains a circuit board, tilt switch and two lithium batteries in place of the mechanical fuze of the conventional Type 72. In both cases, the battery voltage was tested: the two batteries provide 6 volts when new. The first mine showed a voltage of 0.1 and the second 0.26, which would not be adequate for firing. The electrical firing squibs/igniters had more or less disintegrated due to water and were also non-functional." [9] Image: Fenix Insight Ltd.

Another power source used in ammunition is the 'thermal battery' which remains inert until it needs to be used. This is achieved by segregating the components or chemicals until it is activated. One way to achieve this is to retain a liquid electrolyte in a phial, which is broken in order to activate the battery. Another method is to keep the electrolyte in a solid form until it is required, then to heat it up when needed; this is called a 'thermal battery' and is commonly used in shoulder fired missiles. Reserve batteries have extremely long lifespans, because they are generally well protected inside munitions or within robust casings, and deterioration is minimal. Testing of thermal batteries more than 50 years old have shown that they are still capable of functioning correctly and may continue to do so for many years to come.

Shoulder fired air-defence systems such as the Russian SA-7, SA-14, SA-16 and SA-18 missiles use thermal batteries. These are fitted to the launcher and activated by twisting a key at the end of the battery assembly. Once heated up, the battery provides power for a few minutes before it cools and expires permanently. Image: Fenix Insight Ltd.



During the demilitarisation of these missiles a number of SA-7 batteries dating from the 1970s were activated and then tested; all operated correctly. This test shows a Russian 9B17 battery clamped into a vice and activated, producing more than 19 Volts, as it was originally designed to do. Image: Fenix Insight Ltd.

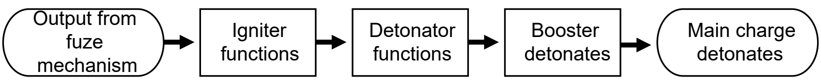


A 9V battery recovered from a victim operated IED in Iraq. The battery is still connected to the crush wire means of initiation. Anecdotally in Syria and Iraq, 9V batteries were estimated to be viable for around 36 months on a victim operated device, and potentially even longer if protected from the elements. Larger motorcycle or car batteries can last for longer still. If the 9V battery is connected to a circuit with a constant power drain, such as a radio controlled device, it may only last 3-4 months. Image: Bob Gravett.

FAILURE OF THE EXPLOSIVE TRAIN

No matter how robust and effective a fuzing mechanism is, it makes little difference if it is unable to trigger the weapon's energetic effect. In most ordnance, this (normally explosive) effect[10] is the result of a chain of events, known as the 'explosive train' in which the output from one component is used to initiate the next. In order to do so, it must supply sufficient energy, or the process will stop.

The explosive chain for a typical high explosive munition looks like this:



Note that the igniter, (sometimes referred to as the primer), and the detonator are often housed in the same component, which may be called a 'detonator' or 'blasting cap' but is more correctly termed a 'detonator assembly' because it usually comprises multiple components within a casing.

This highlights two important points:

1. The operation of any part of the explosive train is potentially dangerous, even if the sequence fails to initiate the main charge. For example, the explosion of a detonator alone could severely damage a hand or eye.
2. The input of sufficient energy from an alternative and unintended source may be sufficient to start or continue the explosive train. For example, a munition being thrown in a fire or hit with a hammer.

"The viability of the explosive compositions concerns issues such as:

- Whether an explosive receptor can be initiated by the designed mechanical input
- Whether a detonator explodes with enough power to propagate to the booster/main charge
- Whether the high-explosive (HE) booster/main charge is capable of detonation." [11]

PYROTECHNIC COMPOSITIONS

Pyrotechnic compositions tend to consist of mixtures of solid oxidising agents and fuels, often comprising both elements (carbon, sulphur and metal dusts) and compounds. Many of the oxidising agents are soluble salts, such as chlorates and nitrates. Reactive metals, such as aluminium and magnesium are also vulnerable to the effects of water.

One of the most commonly used pyrotechnic compositions is gunpowder, or black powder, which is normally used as a propellant or ejection charge but can also be used in pyrotechnic delays. In both roles, the ignition of this charge is often critical to the function of the parent munition, so if is wet or otherwise degraded, it is likely that the weapon will fail to operate as designed. The same applies to the igniters and squibs that are often used to initiate ejection charges.

A Russian OZM-4 bounding mine, recovered from storage in Cambodia. The black powder and igniter (arrow) are still in good condition after 50 years. However, both are vulnerable to water and will fail to function if they are damp. In such a case, the initiation train will be broken and the mine will fail to operate.
Image: Fenix Insight Ltd.

It is possible that a wet pyrotechnic composition, which is incapable of ignition, can subsequently dry out and once again be capable of functioning. This is a rare but important example of a reversable effect of ageing, but one where little hard evidence or research is currently available. Where this does occur, it is also possible that the characteristics of the composition will be altered. For example, a pyrotechnic delay that was designed to last for a few seconds may smoulder more slowly. This introduces more uncertainty to the function of a fuze, and therefore potentially more risk.

Several Yugoslav mines use pyrotechnic ignition compositions in their fuzes, and there are many reports of mines such as this TMA-4 being run over without functioning. This may have been due to the composition becoming wet, but it is possible that the mine might become functional again if the fuze were to dry out. This is a rare and potentially dangerous example of a reversable ageing effect.
Image: Fenix Insight Ltd.

PRIMARY EXPLOSIVES AND DETONATOR ASSEMBLIES

Primary explosives are sensitive compounds that can be initiated by an input from a fuze, such as ignition, impact, friction or electrical charge. Common primary explosives include lead azide and lead styphnate; mercury fulminate was widely used but is rarely seen in modern ammunition. These compounds may be used alone, or in mixtures with other substances (such as barium nitrate, antimony sulphide, and tetrazene) to form ignition compositions. They often form part of a detonator assembly, in which layers of ignition compositions, primary explosives and boosters are pressed into a small capsule.

The capsule is normally made from aluminium, although many other substances have been used, including plastic, steel and cardboard. The choice of material is based on a combination of factors including ease of production and chemical reactivity, which has clear implications for ageing. The open end of a detonator capsule is often sealed with lacquer, a lacquered gauze or a thin metallic foil, all of which tend to be more vulnerable than the capsule itself. Once this material degrades, it may allow water to enter.

The effects of prolonged exposure to water, in the presence of mineral salts and other ageing factors, are not well known. The sensitivity of primary explosives makes practical research dangerous, so little work of this type has been undertaken. However, it is known that mercury fulminate gradually degrades and that lead azide becomes desensitised when damp. It is probable that other primary explosives and ignition compositions also become less sensitive or less powerful when damp. As with pyrotechnic mixtures, this raises the possibility of a component incorporating primary explosive to become non-functional when wet, but regaining its ability to operate when dry. More research is required to fully understand the effect of damp or water saturation on lead azide and lead styphnate in particular and priming compositions in general.

A detonator assembly from an Italian SB-33 mine, laid in the Falkland Islands/Malvinas in 1982 and recovered 35 years later. The hole in the top shows that, at some point, the mine had been actuated and the mechanical components of the fuze mechanism have functioned correctly, driving the firing pin into the stab receptor. But the detonator failed to function and the mine remained unexploded. It is is probable that prolonged saturation or damp has caused this failure. Image: Fenix Insight Ltd.

Even if key primary explosives remain viable, they may become isolated from energetic inputs. This protection may be by displaced components of the fuze housing, by corrosion products, or by other failed energetic components, such as degraded pyrotechnic igniters and delays. This means that a complete high explosive train may be present but remain protected from all but the most extreme energetic inputs, such as severe impact or intense heat.

While lead azide may become desensitized due to moisture, it can become more sensitive if it comes into contact with copper. Especially if moisture is present, copper or cupric azide may form, a primary explosive usually deemed too sensitive for use in detonators. This is particularly an issue in hot, tropical conditions. The risk of using copper for detonator casings has been understood since World War II.[12]

The sectioned body of a Vietnam-era US M904 bomb fuze, recovered in Cambodia. The components of the explosive train are clearly visible running horizontally through the centre of the fuze. Their alignment shows that this section of the fuze was correctly armed. For some reason the striker has not initiated the in line explosive train. The primary explosive may still be viable, as it is well protected by the fuze casing, but the pyrotechnic elements of the explosive train are no longer functional. Note also the zinc and aluminium oxides that have filled the gaps between the steel casings. Image: Fenix Insight Ltd.

SECONDARY EXPLOSIVES

Secondary explosives are the compounds or compositions used in main charges. Some of the more sensitive secondary explosives, including cyclotrimethylenetrinitramine (RDX) and pentaerythritol tetranitrate (PETN), are also used as boosters; these form part of the explosive train and step up the energy from the detonator to reliably initiate the main HE charge. Most common secondary explosive fillings, such as TNT and TNT/RDX mixtures, are extremely stable, so it is rare for these to be the point of failure, although poorly stored TNT though can degrade to the point where it is incapable of reliably sustaining a detonation wave and instead a lower order deflagration event may take place. Poor quality TNT demolition charges have been known to crumble over time, especially in hot storage conditions. Poor quality RDX based C4 explosive charges have also been known to loose cohesion over time as its plasticiser degrades.

Where secondary explosives fail, it is normally because they have become physically damaged or separated. This can happen as a result of fire, when the casing disintegrates, or when pressure from the corrosion products of internal components cause displacement. In these instances, by the time the secondary explosive has been compromised, the munition is likely to be non-functional for other reasons, with numerous points of failure within critical components. Therefore, the failure of secondary explosive is very rarely expected to be the main cause of failure.

TNT fills that are subject to repeated high temperature cycling (above 54°C) may experience exudation.[13] Impurities including 2,4-dinitrotoluene (DNT) can also form.[14] Recent experiments at Cranfield University have shown TNT becomes markedly more sensitive if mixed with grit contaminant, such as iron oxide or quartz sand. Such mixing led to hot spot initiation from lower heights during drop tests.[15] Exuded TNT in high explosive ammunition that has aged therefore presents a potential hazard to EOD operators who should be trained to recognise the signs and ensure such ordnance is handled with requisite care.

A British Mk 5 anti-tank mine in Jordan, with TNT being forced out of the casing by internal corrosion. This is an extremely rare instance where the fuze (to the left of the mine) may still be viable, but the loose structure of the main charge may be unable to sustain detonation. Usually, by this stage the fuze would have suffered numerous points of failure due to ageing. Image: Fenix Insight Ltd.

PROPELLANTS

Propellant is generally absent in UXO because the motor of a rocket or missile is normally fully expended during its deployment, leaving only the warhead ‘unexploded’. The same is true for the propellant used to fire a mortar round or projectile. Propellant is far more likely to be a significant consideration with abandoned ordnance, where all energetic components are likely to be present.

Propellants containing nitrocellulose will decompose whether in the field or in storage. Even if the cartridge casing remains unbreeched, nitro-esters such as nitrocellulose will decompose over time and decompose even faster in hot conditions. The O-NO_2 bonds within the molecules are broken and nitrogen oxides are released. An auto-catalytic reaction can result. It is for this reason that stabilizers are added to absorb the nitrogen oxides before they can attack the nitrocellulose molecules. The stabilizers are consumed over time and the rate of stabilizer depletion governs the lifespan of the propellant.[16] Propellants whose stabilizer is largely or fully consumed may auto-ignite and this is believed to be the possible cause for fires and subsequent explosions at ammunition storage areas (ASA) or explosive stores where older ammunition has been kept. It is for this reason that ammunition technicians conduct surveillance tests on propellant.[17] Safety precautions for storing ammunition are beyond the scope of this guide. However AXO is sometimes stored in ASAs or explosive stores. This is generally not recommended and EOD operators should be aware of the risk this poses, especially for ordnance containing propellant that has been subject to high temperatures in the environment.

Double based propellant removed from debulleted 12.7 x 107mm ammunition. The propellant contains stabilizers to absorb the nitrogen oxides emitted by the degadation of nitrocellulose. Such stabilzers are used up over time and ammunition containing propellant can become a fire hazard. This risk increases in hot environments. It is for this reason that AXO found in the field containing propellant should not normally be stored in an ASAs or explosive stores. Image: Roly Evans.

MULTIPLE FAILURES

The failure of a key component, either within the fuzing mechanism or within the explosive train, will almost always prevent a munition from functioning as designed. In most instances, it will also significantly lower the risk of accidental initiation. In assessing the residual risk of an unexploded or abandoned item of ordnance, there may be doubt in the level of confidence from a single failure. For example, it is common for rusted spring-loaded strikers to become seized into position but, if the spring is still capable of providing power, it is possible that vibration or impact could free the striker and allow it to function.

This Israeli No 4 mine was laid in the Falkland Islands/Malvinas in 1982 and recovered 35 years later. A section through the mine reveals that, although the striker is seized, the remainder of the critical mechanical and explosive components are present and functional. While tests showed this striker could not be made to function due to corrosion and expansion of moving parts, in other instances sufficient vibration or impact could free such a striker. Image: Fenix Insight Ltd.

Where there are multiple points of failure, there can be more confidence in the reduced level of risk. This is particularly clear when there are failures within both the fuze mechanism and the explosive train. For example, in the case of a seized striker, the concern that it might be freed by vibration or impact is mitigated if the detonator assembly (which it would strike) is also non-functional. As each munition ages, and the casing is breached, there will always be one critical component that is the first to fail, but this is often followed in quick succession by others. Among old ordnance, it is common to find numerous points of failure, which limit the possibilities of accidental initiation and therefore decrease the level of residual risk.

The Spanish M-5 is a complex hand grenade incorporating both delay and impact fuzes. This image shows a section through a new grenade, along with aged components from an example recovered in the Falkland Islands/Malvinas in 2015, 33 years after the war. The multiple points of failure among both mechanical and energetic components meant that the risk from the aged grenade was minimal. Image: Fenix Insight Ltd.

AGEING OF IEDS

An IED can in theory be constructed to be highly resilient to the elements. However this is often not the case and most recently observed victim operated anti-personnel mines in the Middle East have been constructed from less robust materials, containing explosives that are more susceptible to weathering than relatively resilient high explosives such as TNT.

Improvised explosive devices often use mixtures such as ammonium nitrate fuel oil (ANFO) or at least a mixture based on ammonium nitrate as the oxidiser. Ammonium nitrate is a common fertilizer but when combined with a fuel is also routinely used as a commercial explosive for blasting purposes. The high volume of gas produced makes ANFO more suited to large scale earth moving than high explosives usually associated with military explosive ordnance. In general many commercial high explosives have a shorter shelf life than military high explosives, although there are exceptions such as pentolite, often used as cap sensitive booster for less sensitive ammonium nitrate mixtures. Other fuels ammonium nitrate can be mixed with include aluminium or sugar. Aluminized ammonium nitrate (AN-AL) is a common home made explosive (HME). Aluminized ammonium nitrate fuel oil (ALANFO) is often used for commercial blasting.

Even when used for commercial blasting ANFO will rarely be stored for more than six months. Other commercial explosive such as nitro-glycerine based powders, or emulsion explosives might have a shelf life of up to twelve months. Detonation cord, now increasingly replaced by nonel shock tube for commercial purposes, might have a shelf life of up to five years, as would cast pentolite. In reality pentolite might have a useful shelf life for far longer. Apart from the latter, most commercial explosives are intended for a short lifespan and are not suitable for use for ordnance that will weather over time, often in conditions of significant temperature change. IEDs that employ mixtures have a high probability of failing due to a failure of the main charge. Military high explosive can easily remain viable for over a century. Explosive mixtures of a fuel and an oxidiser may remain viable for a few months or years.

An expanded aluminized ammonium nitrate charge in a 20 litre plastic container, Jalawla, Kurdistan Region of Iraq, August 2016. Expanded charges would routinely split plastic casings. Image: Bob Gravett.

Ammonium nitrate based mixtures in particular are vulnerable to changes in temperature and saturation. The chemical structure of ammonium nitrate changes once it is heated above approximately 32° centigrade in what is known as a phase transition from Rhombic I to Rhombic II, sometimes also referred to as phases IV and III respectively. Purer forms of ammonium nitrate might experience this phase transition at slightly higher temperatures, (perhaps up to 50° centigrade). Ammonium nitrate based improvised main charges in Iraq and Syria have experienced repeated transition between phases. This results in the generation of fine particles which cake readily through the absorption of moisture. Caking may be thought as changes in the crystalline structure of ammonium nitrate mixture, followed by recrystallisation, especially if moisture is present due to the rupture of the thin plastic casing, or leakage through any threads. Ammonium nitrate also becomes more soluble as the temperature rises. It may have anti-caking agents such as surfactant-stearates but these will not be sufficient to prevent the rapid ageing of ANFO charges. Ultimately ammonium nitrate charges will expand and rupture their casings. While their potential undoubtedly decreases at this point, such charges still pose a potential explosive hazard and should be treated accordingly.

Ammonium Nitrate exudation from the neck of a 5ltr Improvised Plastic IED, Khan Village, Kobane, Syria, July 2016. This main charge was probably emplaced at some point in 2014. It is likely a result of phase changes due to temperature causing expansion and rupturing of the casing at the screw thread. The booster charge was fashioned from knotted detonation cord, which is also prone to hydroscopic action if water breaches the casing. Image: Bob Gravett.

Ageing of ammonium nitrate based main charges may lead to obvious ground sign and easier detection during clearance operations. This image shows IED sinkage in ground due to uncompacted soil exposing the IED, October 2015, Al Hasaka, Syria. Image: Bob Gravett.

An expanded 20 L container containing an ammonium nitrate based charge. Khazir, Kurdistan Region of Iraq, August 2016. Image: Bob Gravett.

Ammonium nitrate HME exudation from a 220mm improvised mortar, April 2015, Kobane, Syria. The mortar contained knotted detonation cord to act as a booster. Detonation cord is susceptible to hygroscopic action. Image: Bob Gravett.

One critical component for IEDs that employ some form of electrical switch, is the longevity of the power source, (often a 9V battery). A typical commercial detonator would have a standard resistance of between 1.45 and 3 ohms. Such a battery might retain sufficient potential to initiate a commercial electrical detonator for up to a few years. Active testing at the point of clearance using an ammeter for batteries is one way to further understanding of these critical components. Detonators may be tested in controlled conditions using approved devices.

Non-electrical means of initiation, such as simple mechanical pressure fuzes sometimes used with devices such as the VS-500 improvised mine are also prone to failure. Ingress of water into the casing will not only affect the main charge if it breaches any protective plastic wrapping but will also corrode the steel fuze components. As with equivalent conventional fuzes it is probably the spring, employed as a holding device, that will corrode to the point of failure first.

Image top shows a heavily corroded improvised mechanical fuze used in the mechanical version of the VS-500. Image bottom shows expansion of the aluminized ammonium nitrate main charge in an electrically initiated VS-500.
Both images: FSD.

Detonation cord knotted to make improvised boosters. Detonation cord, whether military or commercial, is susceptible to hydroscopic action and potential failure in the presence of moisture. Also note the 9v battery linked to the crush wire on the right hand side of the image. Image: FSD.

9v batteries recovered from victim operated IEDs, Iraq, December 2016. How long a 9v battery retains its potential is a key consideration in how long the device remains viable. Image: Bob Gravett.

More research is needed to understand the ageing of improvised explosive mixtures. This includes not only the effect of impurities on ageing ammonium nitrate based charges but also the ageing characteristics of other oxidisers such as potassium chlorate, and potassium nitrate, which became widely used in main charges and propellant in Afghanistan, Syria and Iraq. Such research would possibly require more routine chemical analysis of each main charge. Perhaps the key question is which components tends to fail first, the battery or the main charge? Testing and active reporting of such operational data would enable further research based on evidence.

Improvised explosives such as ammonium nitrate and aluminium mixtures, pictured here in an IED found in Iraq, are far more vulnerable to deterioration than military high explosive. Unlike factory-made munitions, IEDs frequently fail because of the degradation of their main charges. Image: Bob Gravett.

A semi-remote pull on a high explosive 130mm artillery projectile employed as a main charge in an IED, Tel Kaif district, Mosul, May 2022. Use of ERW typically results in IEDs with a far more resilient main charge than those employing improvised explosive mixtures. Image: Daniel Davids.

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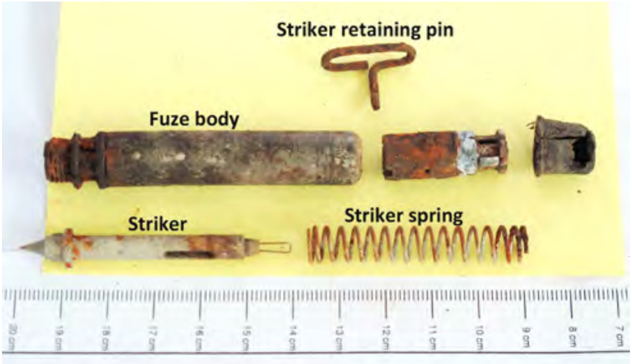
CHAPTER 5
CREATION OF NEW HAZARDS

NEW MECHANICAL HAZARDS

Ageing will eventually lead to the failure of casings, the loss of functionality within fuzing mechanisms and the degradation of energetic materials. However, despite the long-term trend towards reduced function, some ageing effects can lead to a temporary increase in danger. Some of these effects are straightforward and easy to understand, while others are far more complex and unpredictable. Complexity often arises through a combination of effects, where the number of factors in play means that there are many permutations or possible outcomes.

A simple example of a potentially hazardous effect would be a striker retaining pin rusting through. If this pin were the only component retaining a spring-loaded striker, then its weakening might make the fuze far more unstable. But this scenario ignores a number of other parallel effects, most of which would be making the fuze safer. These might include:

- Seizing of the striker within the fuze body
- Weakening of the striker spring
- Blunting of the firing pin
- Failure or desensitisation of the detonator assembly.



An aged Russian MUV-2 fuze is a simple illustration of a potential increase in danger, as the striker retaining pin corrodes and weakens. However, in many such fuzes, other effects, such as the seizing of the striker into the fuze body and weakening of the striker spring, are also occurring. These increase the likelihood of failure and may offset the hazard associated with the retaining pin. Image: Fenix Insight Ltd.

In this example, an increase in danger would mean that the retaining pin would have to be vulnerable while most, or all, of the other components would have to remain in good condition. In practice, since all components would be close together and subject to the same ageing influences, these other components would have to be highly resilient. If that were the case, then this scenario might be foreseeable.

A PMN mine found in Cambodia, December 2006. The PMN has a cocked striker with a plastic holding device held in position by a vertical spring. As this vertical spring degrades the mine can become even more sensitive to movement. Eventually the striker assembly of the mine will also corrode diminishing the risk of the mine initiating if moved. As the PMN ages the risk it presents changes over time. Image: Sean Moorhouse.

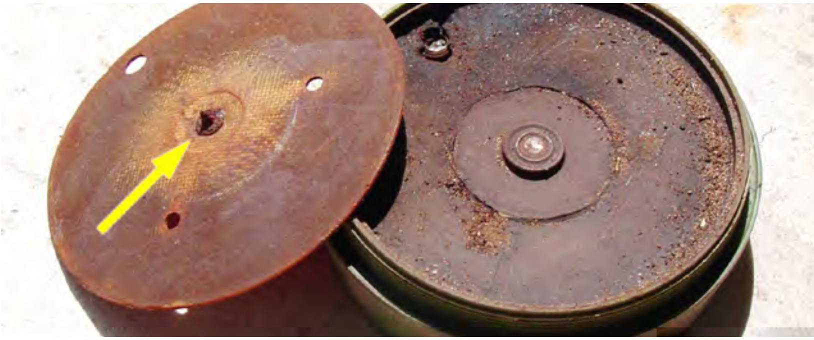
A corroded and broken detonator rotor spring in the fuze of a PTAB-2.5M submunition. Here, the fuze is seen armed, with the rotor central. However, the absence of the spring means that the rotor can now move by gravity or turning moment. Once the arming action has freed the rotor, it is a question of chance whether it remains out of line or falls into line. The orientation of the fuze is not visible from the outside, nor is it possible to see the position of the rotor. This means that it may alternate between being armed and unarmed as it is moved. Corrosion of the rotor spring has made this item more dangerous. Image: Fenix Insight Ltd.

Some fuzes rely on springs or the strength of a casing to provide resistance to actuation. In the case of a landmine, a spring or casing may be used to bring the operating pressure up to an acceptable threshold. In a projectile fuze, a spring or collapsible section of the casing may require a certain level of impact for initiation. In either example, the degradation of the casing or spring might significantly lower the operating threshold, making the fuze more sensitive. Once again, whether a munition becomes more hazardous under these circumstances also depends on whether other critical components remain functional. There may be a period where this is the case, eventually followed by the failure of a key component, which then prevents the operation of the mechanism.

The Russian AM-A fuze is extremely simple, with a firing pin positioned in line with a detonator and with no safety or arming mechanism, just a block as a holding device that is crushed on impact. The front of the fuze casing (circled in red) is designed to protect the firing pin, but also has the thinnest section of steel (where it is designed to collapse or shear). If this section of the casing were to disintegrate, the firing pin would be more vulnerable to impact, and the fuze would become more sensitive. AO-1SCh submunitions using AM-A fuzes were known to have high failure rates when employed in Syria. Image: Fenix Insight Ltd.

DETECTION OF METALLIC COMPONENTS

A different form of hazard can arise as the result of ageing with minimum-metal mines. The threshold of many modern metal detectors is typically in the region of a tenth of a gram of ferrous metal, at a depth of approximately 100 mm. As metallic components in minimum metal mines corrode, they become harder for electro-magnetic induction (EMI) equipment to detect. This is due to a decrease in the conductivity of the metal as it oxidises. Iron oxide is a poor conductor of electricity. Some minimum-metal mines, such as the Belgian M35, the Chinese Type 72 and the United States M14 contain sub-gram quantities of steel, which are prone to rusting. When this metal corrodes, it is no longer practically detectable. If enough of the firing pin remains to cause initiation, then there may be a dangerous combination of an 'undetectable' mine which is still operational.



The Chinese Type 72 anti-personnel mine has a firing pin (arrow) weighing just 0.12g, which makes it barely detectable. Any significant loss of metallic mass, as the pin rusts, may take it below the detectability threshold, even though the pin may still be long enough to fire the stab-sensitive igniter. This may have been the case with some of the mines examined in Cambodia in 2015. Image: Fenix Insight Ltd.

Another example is the P4B minimum metal mine found in the Falkland Islands/Malvinas. The mine contains a stainless steel spring that acts as a holding device between a plastic striker and the stab sensitive detonator. Depending on the year of production, the detonator will have a foil (lead/tin/antimony) cover, and for versions made in 1980, the actual detonator capsule will be made of aluminium. All these metallic components will influence how easy the mine will be to detect. As any of these components oxidises, their conductivity reduces and the mines of which they are a part become even harder to detect.

Springs from P4B minimum metal anti-personnel mines, one corroded, another not. The corroded spring's conductivity will reduce making the mine harder to detect. For minimum metal mines, corrosion of the only metallic components makes them even harder to detect. Image: Fenix Insight Ltd.

NEW EXPLOSIVE HAZARDS

The majority of new hazards involving the ageing of energetic compositions appear to arise because of chemical reactions, leading to the formation of more sensitive compounds. Most of these involve the primary explosives used within the fuzing system, but a few also involve secondary explosives.

NEW HAZARDS INVOLVING SECONDARY HIGH EXPLOSIVES

There a several well-known areas of risk, such as the reaction between certain high explosives and alkalis. “As a rule, it is inadvisable to allow high explosives to come into contact with substances of an alkaline nature - in extreme cases highly sensitive reaction products may be formed with a consequent increase in the chance of accidental ignition.”[1]

The reactions of picric acid (trinitrophenol) with metals such as iron, lead and copper are well documented, and are considered a major safety issue when dealing with German bombs from World War II. Picric acid was frequently used as a booster at the base of the fuze and can form sensitive compounds in and around the fuze pocket and the head of the fuze. “Picric acid readily forms salts on contact with many metals (including copper, lead, mercury, zinc, nickel, and iron) that are more sensitive explosives than picric acid itself when subjected to heat, friction, or impact.”[2] It is for this reason that fuze immunization techniques use saline solution in order to desensitize any picrate salts present in a fuze pocket. Picric acid can even form calcium picrate, a sensitive compound, if exposed to cement. [3]

Physical effects (rather than the chemical reactions mentioned above) can also affect the sensitivity of explosive. These are reported to include the effect of recrystallisation after explosive has melted. British Royal Engineer EOD personnel are taught that they should be cautious of recrystallised TNT, when it forms after procedures to steam out molten explosive from World War II bombs. The basis of this assertion is unknown, but it is believed to relate to the needle-like crystalline structure of the newly solidified explosive.

Research does confirm that both temperature and contamination can increase the sensitivity of TNT (and probably other high explosives). Partial melting can occur in some regions through high ground temperatures or brush fires, while sources of contamination may include the melted lining of bomb casings (often pitch or asphalt) or soil and other debris driven into the explosive during impact. "The research demonstrated that asphalt-contamination of recovered TNT does not appear to have a significant effect on TNT shock sensitivity, but does adversely affect impact and thermal sensitivity. The results also showed that molten TNT seems to be more shock sensitive than previously suspected."[4]

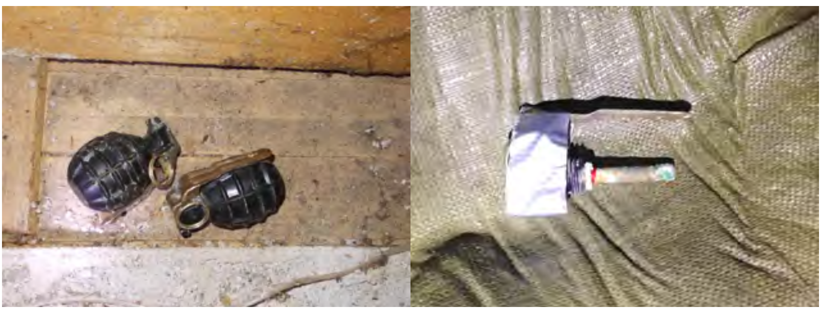
NEW HAZARDS INVOLVING PRIMARY HIGH EXPLOSIVES

One possible consequence of primary explosives ageing is a decay product of lead azide, hydrogen azide HN_3, which can react with metals such as copper, zinc and cadmium, or their alloys, to form highly sensitive explosive compounds. Within normal ammunition lifespans, this is managed by the sealing of the detonator capsule (to prevent the ingress of moisture and other contaminants). Ageing tends to lead to the corrosion of the detonator capsule, allowing the primary explosive to begin to degrade and the escape of hydrogen azide. The aluminium liner can also corrode, permitting direct contact between hydrogen azide and the inside of the detonator capsule. This creates a mechanism for the formation of sensitive compounds within the fuze mechanism.

Copper or cupronickel shells or liners may still be employed for use, mostly in commercial detonators but also possibly in military ones . The lead azide is separated from the shell by an aluminium liner, but physical damage or corrosion over time, may allow the lead azide to come into contact with the copper.[5] Especially if moisture is present copper azide crystals may form. This presents a significant hazard. A possible tell-tale sign can be the presence of a blue mouldy verdigris compound, although identification of such a compound does not automatically mean copper azide is present. If present EOD operators should be extremely cautious. Testing for the presence of copper azide is particularly important for ammunition stored in hot-wet (tropical) conditions and ammunition surveillance should include regular checks for this.

In July 2016 a fatal accident occurred during mortar firing exercise in Mali. The subsequent accident investigation report identified formation of copper azide in slightly corroded Bulgarian variants of the M-6 mortar bomb fuze as a potential factor in the accident.[6] In this case, it was suspected that copper azide had formed through the reaction of lead azide with the copper components of the brass slide (in which the detonator is housed). The Dutch investigation was thorough, but as in many incidents involving explosives, the exact cause was often not conclusively established. Accidents attributed to the degradation of primary explosives are rare, but it is possible that a proportion of unexplained detonations are associated with this effect.

A photo from the Dutch Safety Board accident investigation showing green copper azide crystals (circled) inside the casing of an M-6 mortar bomb fuze. The formation of this sensitive compound is believed to have caused a fatal accident in 2017, and could become a hazard in many types of ammunition as it ages.
Image: The Netherlands Organisation for Applied Scientific Research.



Two M-75 grenades retrieved during an EOD task. While the grenades look to be in reasonable condition, removal of the fuzes revealed corrosion of the detonator casing, probably caused by humidity over time. While not confirmed, it is possible that the blue substance is some form of verdigris. Images: Private.

ENVIRONMENTAL IMPACT

The effect of soils on ordnance deterioration is highlighted in earlier chapters, but there can also be a reciprocal effect. Once the casing is breached, chemical elements and compounds within a munition can leach into the surrounding soil and water to cause contamination. For projected or propelled land service ammunition the breach may occur on impact, as a result of impact from agricultural machines or from deterioration due to ageing.

RDX and TNT, the common high explosive fills used in most high explosive ordnance, can both exhibit a degree of toxicity. For example, the nitro aromatic TNT can biodegrade to the 2,4 DNT isomer. DNT is listed by the United States Environmental Protection Agency (EPA) as hazardous waste,[7] and is highly toxic to humans. RDX has been designated a possible human carcinogen by the EPA, with advisory limits for HMX, RDX and TNT.[8] [9] RDX has a greater propensity to contaminate groundwater since it does not bind to organic matter in the earth as TNT and DNT do.[10] Testing of military firing ranges over time suggests that contamination tends to stay in the topsoil, approximately the first 30cm, depending on the soil type.[11] [12] [13]

Explosive ordnance that ages in the environment can in certain circumstances pose a hazard to that environment. However these risks should not be misrepresented. Much depends on the amount of energetic exposed, and the surrounding soil conditions. For example TNT fills in organic soils tend not transport and therefore don’t necessarily pose a significant pollutant risk in that context. However in sandy soils with less organic matter such a transport risk may be applicable.[14] Individual items of ageing explosive ordnance that may leach into the soil are less of a risk than persistent open detonation on demolition ranges, where the potential for residue loading is greater is increased.

Lead from small arms ammunition (SAA) poses a particular pollution risk. Lead slag is classified as Toxic Solid UN 6.1 (UN ID 3288).[15] Lead is an amphoteric metal that exhibits its greatest solubility in acidic ($pH < 4$) and heavily alkaline ($pH > 11$) solutions.[16] Practically this means that “lead corrodes and leaches readily in acidic conditions to concentrations that can exceed guidelines for human health and controlled waters.”[17] Individual ageing bullets scattered around a former battlefield might not be as significant a risk as large quantities of SAA left as AXO in one place.

Liquid propellants perhaps pose a more immediate risk to the environment. The SA-2 missile has a solid fuel booster and a liquid sustainer that includes red fuming nitric acid as an oxidiser and a mix of triethylamine and isomeric xylidine as the fuel; all are toxic. Fuelled sustainer motors that are left to age pose a significant risk.

An SA-2 missile in Iraq following the war. Liquid fuel and oxidant from the rocket motor is leaking and contaminating the ground. Image: Fenix Insight Ltd.

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CHAPTER 6
CASE STUDY – THE NETHERLANDS AND DENMARK

In 1945 minefields in both Denmark and the Netherlands, along the Atlantic Wall and inland, were subject to rapid clearance. While the clearance was swift, time was taken to analyse clearance in a way that had not been done before. Included in this analysis was a review of the ageing characteristics of a range of German mines in different environmental conditions in the Netherlands. This is possibly one of the oldest recorded attempts to systematically record the ageing characteristics of mines in the field. Further understanding of how German mines from World War II age over a longer period was provided when the final minefields in Denmark, on the Skallingen Peninsula, were cleared up to 2012.

AGEING OF MINES CLEARED IN 1945 IN THE NETHERLANDS

In 1945 a Military Operational Research Unit conducted a study of Minefield Clearance and Casualties. As part of this study they included "an attempt" "to study the effect of damp and rust on the various components of mines, after periods of exposure from six months to two years in different types of ground." What resulted was a summary based on anecdotal "reports received from the Engineer Brigade Draeger, and the British Engineers in charge of supervision and from general observation."[1] While there are limitations to this general approach, since reports were not made of the ageing characteristics of each individual mine, it still stands as a remarkable overall analysis where observations of approximately 480,000 cleared mines were recorded.[2]

Mines found were broadly disaggregated into metal and wooden cased anti -personnel and anti-tank models, and the areas they were found into broadly disaggregated into three: "Sandy and Dry Earth, "Low Lying Meadows" and "Polderland". It should be noted that the Germans tended not to lay mines directly onto beaches, but only affixed mines to obstacles on the beach. These, and any mines laid in coastal marshes, are the only mines that would be directly affected by seawater. Laying of minefields, especially on the Atlantic Wall, started in 1943, with many laid in early 1944. Minefields were also laid inland as the front lines moved across the Netherlands from September 1944.

For metal cased anti-tank mines, such as the various Tellerminen, it was observed that these "stood up to the most severe conditions of weather and site remarkably well. Under very damp conditions, rusting of the outer cases was general but there was hardly any loss of efficiency after two years."[3] For more exposed external parts it was observed that "the wires of booby-trapped mines were often rusted through and pull igniters (such as the ZZ-42) used as anti-handling devices became ineffective after long exposure to severe conditions due to damp penetrating the firing cap and rusting the spring."[4] Tellermines affixed to beach obstacles, if "protected with good tar paint were found to be effective after six months immersion in sea water." British anti tank mines tended to have thinner casings and the explosive fills such a TNT or Baratol could be affected once the case was ruptured. "The explosive in about 10% of *British* (sic) mines showed some signs of sweating after about one year in the ground."[5] For anti-personnel mines it was found that the key point of potential failure was the fuze and detonator assembly. This was often referred to at the time as the igniter, the most common being the ZZ-42 found in the Schumine. "The high percentage of ineffective igniters was due almost entirely to damp penetrating the firing cap and rusting the spring."[6]

Wooden mines were found, as expected, to be more susceptible to damp. "Casings began to show signs of deterioration after six months in reasonably dry ground and after two to three months in very wet ground. Conditions of warping, swelling, laminating and general disintegration of wood inevitably followed in the next few months."[7] Mention was also made of British detonators, with No.27 detonators with copper casings being more resilient to damp than No.8 detonators with aluminium. However, copper is no longer used for detonator casing due to the potential to form copper azide,[8] a primary explosive with extreme sensitivity unsuitable for any application.[9]

TABLE 6

BEHAVIOUR AND EFFICIENCY OF MINES AND COMPONENTS IN DIFFERENT SOIL CONDITIONS

Type of Mine	Part of Mine	Sandy and Dry Earth	Low Lying Meadows	Polderland which has been inundated since the mines were laid
METAL A/T MINES	Casings	100% effective after 2 years Rusting: Strong in coastal areas but not severe elsewhere. No loss of efficiency.	100% effective after 18 mths. Rusting after 12 mths with no loss of efficiency.	100% effective after 6 mths immersion. Rusting: General with no loss of efficiency.
	Igniters and Fuses.	90% effective after 2 years. Damp penetration to fuse pocket without loss of efficiency.	Teller igniters 90% effective after 1 year. Pull igniters (ZZ35, DZ 35 and DZ 42) used as anti handling devices 70% effective after 3 mths due to damp penetration of firing cap and rusting of the spring All English A/T mines 100% effective after 10 mths.	Teller igniter 80% effective after 3 mths immersion due to water penetrating cap and rusting spring. British A/T igniters 30% effective after 3 mths immersion.
	Detonators.	100% effective after 18 mths.	Over 90% effective after 6 mths.	90% effective after 3 mths immersion.
METAL A/P MINES	Casings.	98% effective after 12 mths. Exteriors completely rusted after 6 mths. 98% efficient due to rusting between inner and outer casing causing failure to jump.	As for column 3 but with slightly increased percentage ineffective.	Strong external rusting without loss of efficiency. Failures due to water affecting firing mechanism and propellant charge in addition to those in column 3.
	Fuses and Igniters.	70-90% effective after 6 mths (almost all due to damp penetration of firing cap).	As for column 3 but percentages decreased to 50% effective. ZZ35 40% unserviceable after 8 mths even if protected. 70% u/s if not protected.	80-90% unserviceable after 2 mths immersion. As for column 4.
			Buck chemical igniter unserviceable after 6-8 mths due to chemical decomposition.	
Wooden Mines	Casings	Plywood: Deterioration after 6 mths. Lamination after 12 mths. Impregnated Hardwood: 80% effective after 12 mths. General: 10% unserviceable after 6 mths due to warping and swelling of wood.	Plywood: Lamination after 4 mths. only 60% effective after winter in ground. Impregnated hardwood: 75% effective after winter in ground. Causes: Warping and swelling of wood.	20% effective after 2-3 mths.
	Fuses and Igniters	Damp penetration of firing cap and rusting of pins generally. 10% pins rusted after 4-5 months 45% pins rusted after 6-8 mths.	As for column 3 but percentages as high as 80% after 6 mths.	Almost completely ineffective after 2 months immersion.
	Detonators	10-20% unserviceable after 6 mths.	40% unserviceable after 6 mths.	60-80% unserviceable after 3 mths. immersion.

Table 6 from Military Operational Research Unit Report No.7 Battle Study summarising the ageing effects on both metal and wooden cased mines in "Sandy and Dry Earth, "Low Lying Meadows" and "Polderland". The observations are consistent with more recent analysis of ageing of explosive ordnance.[10]

Tellermine-42s being removed from beach obstacles using clearance drills acceptable at the time. Tellermines coated in tar were found to be resilient to seawater for up to six months. Image: NIOD Institute

Inspecting Tellermine-42s removed from a "low lying meadow". While rusting was observed in this environment after 12 months, metal cased Tellermines were still deemed 100% effective after 18 months. Image: NIOD Institute

AGEING OF MINES CLEARED UP TO 2012 IN DENMARK

In 1945 personnel cleared approximately 1,389,281 mines from an area of 1,103.2 km².[11] One area, on the Skallingen peninsula near Esbjerg, proved too difficult to reliably clear due to shifting sands and was left until efforts resumed in the 2000s. It was estimated that up to 72,000 mines remained at Skallingen. Clearance was finally completed in July 2012. During the modern efforts to clear the remaining mines particular attention was paid to how items had aged over approximately seven decades. As with the analysis in the Netherlands in 1945, note was taken of the different conditions mines aged in, even within a small geographical area. These included an area regularly subject to tidewater, including salt marsh. Sediment in salt marshes can have low pH levels, though in the case of Skallingen this was not the case, perhaps because of the mineralised clay soil type present, and the clearance teams concluded it that did not affect the decomposition. In addition a significant proportion of mines were found in sand dunes, often meters below the surface. Drainage within the sand dunes meant mines there that were above the water table were left unsaturated.[12]

The mines and mine components found at Skallingen were chemically analysed by the Netherlands Organisation for Applied Scientific Research using x-ray diffraction techniques. Analysis of 33 detonators with aluminium casings showed that the lead azide and tetryl fills had altered to lead carbonate hydrate and lead oxide, making them non-functional. For the percussion caps themselves, many were corroded to zinc oxide, again making them non-functional.[13] Nevertheless a test of 12 detonators found that 50% of those found in the sand dunes (i.e. not exposed to water) were still functional.[14] Detonators from the marsh were all inactive.

Mechanical cocked striker fuzes like the ZZ-42, used in Schumines, Stockmines and Holzmines, were routinely found at Skallingen. The bakelite body of the fuze had retained its form despite prolonged weathering. Some metallic parts were still protected by an oil coating, however exposed firing pins were invariably heavily corroded.

A stockmine with ZZ-42 igniter found buried in the sand dunes at Skallingen, September 2006. While the mine body, consisting of metal fragmentation embedded in concrete, has proved very resilient, with the paint still showing, and the bakelite fuze body is intact, the exposed part of the striker has heavily corroded. The fuze is no longer functional, although it could still pose an explosive hazard.
Image: Martin Jebens, Danish Coastal Authority.

Most wooden mines were found with the wood fully corroded, although there were some notable exceptions for ones buried in the sand dunes. All metal anti-vehicle mines were found corroded but nevertheless intact and in relatively good condition in the dunes and sometimes even in the marsh. Notably when wooden cases had corroded, the TNT explosive fills had shown minimal decomposition. TNT blocks from Schumines were routinely found in the dunes with ZZ-42 igniters still attached but the wooden casing decomposed. TNT is relatively insoluble especially as pH increases.[15] The sand of the dunes has a higher pH than the salt marsh and this, along with drainage, and perhaps the protection of the wax paper, have enabled these TNT block to survive as well as they have.

A Holzmine-42 found deeply buried in sand dunes, Skallingen. Such was the lack of corrosion to some wooden mines found in sand dunes that it was not uncommon to even find paper markings still intact, such as this label found in September 2010, showing a date of manufacture of February 1944.
Images: Martin Jebens, Danish Coastal Authority.

A Tellermine-42 found heavily corroded but intact. Being buried under a meter of sand has largely protected the mine for over seven decades.
Image: Martin Jebens, Danish Coastal Authority.

Wooden Schuminen have corroded leaving just the 200g TNT blocks in wax paper and the ZZ-42 fuzes. Note the bakelite fuze body is still in remarkably good condition but the steel striker and retaining pin have corroded. TNT has a relatively low solubility, as shown by the relative resilience of these charges, albeit these have not been subjected to prolonged saturation in salt water. Images: Martin Jebens, Danish Coastal Authority.

This is a brief summary of extensive work analysing the ageing characteristics of mines found in Skallingen. Nevertheless what was observed correlates with the general observations of this guide. Over time, the functionality of landmines seems to depend on the environment they are placed in and the composition materials. There is no hard and fast rule concerning the ageing of explosive ordnance including landmines. However there are likely characteristics. Skallingen showed characteristics of the ageing effect in salt marsh and dunes, and revealed how, especially in dunes, the ageing process can be retarded to a remarkable degree.

ENDNOTES

1 The National Archives. Military Operational Research Unit Report No.7 Battle Study. Minefield Clearance and Casualties. CAB 106/1023: 17

2 The National Archives. Military Operational Research Unit Report No.7 Battle Study. Minefield Clearance and Casualties. CAB 106/1023: 17

3 The National Archives. Military Operational Research Unit Report No.7 Battle Study. Minefield Clearance and Casualties. CAB 106/1023: 17

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5 The National Archives. Military Operational Research Unit Report No.7 Battle Study. Minefield Clearance and Casualties. CAB 106/1023: 18

6 The National Archives. Military Operational Research Unit Report No.7 Battle Study. Minefield Clearance and Casualties. CAB 106/1023: 18

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8 Defence Technical Information Center. Study of the Action of Lead Azide on Copper. (Picatinny Arsenal, 1942)

9 Royal Society of Chemistry. H Maximilian Advancement and stabilization of copper azide by the use of triazole – and tetrazole ligands – enhanced primary explosive. (Material Advances, November 2021): 579

10 The National Archives. Military Operational Research Unit Report No.7 Battle Study. Minefield Clearance and Casualties. CAB 106/1023: 19-20

11 Centre for International Stabilization and Recovery, R Evans, "Lessons from the Past: The rapid Clearance of Denmark's Minefields in 1945." (James Madison University, 2018): 19

12 Centre for International Stabilization and Recovery, M. Jebens, "Environmental Impact on the Functionality of Landmines : Does Aging Matter? " (James Madison University, 2010): 74

13 Centre for International Stabilization and Recovery, M. Jebens, "Environmental Impact on the Functionality of Landmines : Does Aging Matter? " (James Madison University, 2010): 74

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15 Journal of Chemical and Engineering Data. S Kyoung. "Solubility of 2,4,5-Trinitrotoluene (TNT) in Water." (ACS Publications, 1996): 758-761

CHAPTER 7
CASE STUDY – PACIFIC ISLANDS

Many islands in the western Pacific saw extensive fighting during World War II. For example the Solomon Islands Campaign of 1942-1945 left behind extensive ERW contamination. The ordnance that remains is mostly Japanese or American but can also include British or Australian ammunition. After the war there was no large scale clear up effort as occurred in parts of western Europe. Much remains as it was left during the conflict eight decades ago. ERW continues to pose a threat to the local population. This short case study will show brief examples of the condition of ordnance recovered in recent years, with observations on the ageing characteristics of that ordnance.

A Royal Solomon Islands Police Force (RSIPF) EOD team and local villager, Willy Basi inspect 69 mortar rounds left by an old mortar position south of Honiara in the Solomon Islands. This AXO has stayed in this position since it was abandoned in 1942. While the fuzing has not been armed the ordnance has noticeably aged and still poses a hazard to the local population. Image: John Rodsted.

ENVIRONMENT

Many islands where fighting occurred have a tropical climate. For example almost all of the Solomon Islands, except for the area from northern Guadalcanal to the Nggelas and possibly southern Isabel can be classified as 'continuously wet' (over 40 weeks per year with more than 5 cm rain per week).[1] The temperature is relatively uniform, ranging from 22°C to 31°C throughout the year. Humidity is highest in the mornings, and regularly reaches 90 per cent.[2] A high proportion of the islands are coastal and therefore affected by salt, causing accelerated corrosion, particularly of ferrous metal casings.

A fired Japanese Type 91 15.5 cm HE projectile, showing heavy external corrosion. UXO such as this can be found on the surface or buried. Impact into abrasive soil removes much of the surface paint or other coating and scratches the metal, encouraging the corrosion process to proceed quickly. Nevertheless the thickness of the steel casing can mean that while the external appearance is very weathered, underneath the layer of corrosion both the steel casing and TNT main charge are in surprisingly good condition. Image: Len Austin

A Japanese 15 cm Type 13 or 88 Common projectile, showing deep corrosion from exposure to seawater. The copper driving bands are now green due to the copper salts produced by chemical reaction with the local environment. The smooth driving bands indicate that this projectile has never been fired. This classifies it as abandoned (AXO) rather than unexploded (UXO) explosive ordnance. While its fuze may be considered not armed, AXO still poses a significant explosive hazard. It can be misused by fishermen. In other countries AXO has frequently been employed as a main charge in IEDs. Image: Len Austin.

A shallow-buried Japanese Type3 No25 Mk8 Bomb Mod1 – 4, recovered in relatively good condition with the tail fins still intact. Between the fins, at the rear of the bomb casing, is the remains of the tail fuze, no longer functional. Image: Len Austin.

Recovery of Japanese bombs from a buried stockpile. These Type 3 No25 Mk8 Mod1 – 7 bombs are unfuzed, with just a blanking plug fitted into the fuze wells. The absence of a fuze and primary explosive reduces the risk significantly. While a degree of corrosion can be seen, the resilience of the thick cased munitions is evident. Image: Len Austin.

A Japanese Type 3 Sea Mine, presumed to have been washed up on the shore and subsequently buried in sand. Image: Len Austin.

The combination of abrasive sand and salt water has accelerated the corrosion of the casing, which has partly disintegrated, leaving the explosive filling exposed. Image: Len Austin.

EXPLOITATION

A portable cutting deck, based on a commercial bandsaw, conducting exploitation of Japanese 75mm Type 94 HE projectiles. While not a conventional ammunition process facility, mobile cutting stations can still conduct exploitation safely by effectively controlling the surrounding around as a range. All cuts are conducted remotely. The TNT fill is ultimately disposed of by open burning. Image: Len Austin.

The team inspects a cut made on a 75mm Type 94 HE projectile. Where possible, the cut avoids sensitive components and exposes the maximum diameter of filling. Cutting also allows the internal condition of the munition to be assessed. On this item the uneven corrosion of the steel casing can be seen. Image: Len Austin.

Even large bombs, such as this Japanese Type3 No25 Mk8 Mod1, can be remotely cut using the adapted bandsaw rig, if the state of the fuze enables the bomb to be moved. This allows the high-risk fuze components to be separated from the main charge, while giving access to the explosive so that it can be burned out. The fuze section can be left nearby, so that the heat also destroys the primary explosive, which detonates harmlessly. Image: Len Austin.

Cuts through 75mm and 15cm projectiles show that, despite the external corrosion, there is still plenty of unaffected steel. The yellow explosive filling is based on TNT, which darkens to a brown colour when it is exposed to light. Image: Len Austin.

Projectiles that have been cut and inspected await final disposal. Image: Len Austin.

DISPOSAL

A Japanese Type3 No25 Mk8 Mod1 bomb, which has been cut in half. The explosive has then been burned out from both halves to leave the empty steel casings. Once checked to ensure that no hazardous material remains, the scrap steel from these operations can be recycled. In some regions, this process helps to pay for the clearance work. Image: Len Austin.

Another view of the burned-out Japanese Type3 No25 Mk8 Mod1 bomb. In the centre is the nose cone, which contains the fuze. This has been cut off separately to ensure that explosion of the fuze cannot detonate the main charge in the larger sections. By the time the fuze gets hot enough to explode, the majority of the secondary explosive in the nose cone has already been consumed, and the small quantity of primary explosive inside detonates harmlessly. Image: Len Austin.

SUMMARY

The climate and environment on tropical islands in the Pacific has accelerated the effects of ageing of the ordnance that remains from the World War II. The combination of water, salt, abrasive sandy soils and warm temperatures have provided conditions that promote ageing. Mechanical cutting techniques using mobile platforms have been used to assess the ageing of explosive ordnance and assess the internal condition.

Lightweight and thin-cased munitions are encountered less frequently in recent years. It is believed this is due to thinner casings being more vulnerable to complete disintegration. Heavier cased munitions, such as aerial bombs and projectiles, continue to be found and are, as expected, usually severely corroded on the surface. However, cutting reveals that most still have a substantial thickness of unaffected iron or steel casing, which has effectively protected the main charge. The secondary explosive remains viable, but the condition of primary explosive components is largely unknown. Steel cased ERW, designed to undergo significant forces on firing or dropping, and also designed to provide extensive fragmentation on detonation, are remarkably resilient, even in an environment like the Solomon Islands. It is likely that the residual risk from AXO and UXO to the population of the Solomon Islands will continue for several decades.

Sporadic accidents among the local population confirm that the ordnance remains dangerous and is capable of detonation if mishandled. This energy may be in the form of a violent impact, such as a hammer blow, or intense heat, such as that experienced close to an open fire. Explosives from ERW have also been misused for fishing purposes. The level of energy required to initiate ERW depends on the presence and viability of primary explosives within the fuzing system. If these are present and functional, then the energy input required for initiation is likely to be substantially lower than that needed to initiate an unfuzed secondary explosive filling.

ENDNOTES

1 J Hansell and J Wall, Land Resources of the Solomon Islands. (1976)

2 T Leary, “State of the Environment, Solomon Islands” United Nations. (1993): 3

CONCLUSION

Many of the day to day activities of mine action, from clearance of minefields to bulk demolitions of AXO or stockpiles, require accurate assessment of explosive ordnance. Understanding how explosive ordnance ages and the evolving risk it poses is necessary for such assessments. Ageing is also pertinent to how anti-personnel and anti-vehicle mines may be detected, especially minimum metal mines. It is also relevant to correctly identifying explosive ordnance since its appearance can change significantly as it ages in the environment.

The design and construction of the item is naturally key in how it ages in a given environmental circumstance. Since breaching of the casing is typically a critical point in the ageing process, it follows that ordnance with thinner casings such as mines, missiles and rockets are more susceptible. There are exceptions of course, with certain well-constructed plastic anti-vehicle mines proving remarkably resilient in challenging environments such as the Falkland Islands/Malvinas. While thick metal cased artillery projectiles, mortar rounds or aerial bombs will corrode, examples from northern France and Belgium to the Solomon Islands confirm just how resilient the encased high explosive main charges of such ordnance are. The means of initiation may well be non-functional, but the items remain explosive hazards that if mishandled present a significant risk.

Logically, explosive ordnance also ages according to its environment. The thin plastic cased anti-personnel mine subject to sunlight and therefore UV damage will invariably age faster than thick metal cased ammunition encased in clay. Even in the same area, the wooden cased mine might survive in well drained sand dunes, but age rapidly in a nearby salt marsh.

Whilst ageing can be evident from the exterior of an item of explosive, it should always be assumed that until the interior can be assessed through professional exploitation, unseen changes have taken place. For example, a fuze may look in a viable condition, but humidity over time may affect pyrotechnic elements within. Internal mechanical elements may degrade faster than the casing and in certain circumstances this might make the ordnance more sensitive to handling.

The guide aims to provide an overview of a complex subject. The task of researching ageing of explosive ordnance and risk continues. The failure of IEDs due to ageing is likely to be significantly faster than in most manufactured ammunition, especially if improvised explosive mixtures and electrical initiation from commercial batteries are used. Further research would provide more evidence and increase our understanding of this. As insensitive munitions become more commonplace, the ageing characteristics of new energetic formulations will also merit research. Additional study of how prolonged saturation affects primary explosives in detonators would also enable more important understanding. Underpinning any such research should be more extensive operational data gathering in the field, so that ageing characteristics and context are routinely recorded in a standardised way. Mine action operators may also wish to consider including more on the ageing of explosive ordnance in their respective EOD training courses. EOD operators are almost certain to find explosive ordnance that has aged in some respect and a general understanding would assist them in the conduct of their tasks.

A British 4.5inch artillery projectile found in a field close to the Thiepval Memorial, Somme, France, January 2023. Despite being in the ground for over 100 years the projectile is in remarkable condition. Note the relative ageing of the driving band compared to the casing. Image: Quentin Naylor.

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