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Scoping Study of the Effects of Aging on Landmines phase 2

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Abbreviations List

AP(M)	Anti-personnel (mine)
AT(M)	Anti-tank (mine)
ATR-FTIR	Attenuated Total Reflectance-Fourier Transfer Infrared Spectroscopy
BSE	Back-scattered electron
CISR	Center for International Stabilization and Recovery
CMAC	Cambodian Mine Action Centre
CKA	C King Associates Ltd
CV	Coefficients of variation
EC	Electrical conductivity
EDS	Energy-dispersive spectroscopy
EDX	Energy dispersive x-ray
EPDM	Ethylene propylene diene Monomer (M-class) rubber
ERW	Explosive remnants of war
EOD	Explosive ordnance disposal
DL	Detection limit
FTIR	Fourier Transform Infrared Spectroscopy
GWHF	Golden West Humanitarian Foundation
NCDR	National Committee for Demining and Rehabilitation
HE	High explosive
ID	Influence diagram
IED	Improvised explosive device
IR	Infrared
JAF	Jordanian Armed Forces
JMU	James Madison University (location of the CISR)
LSM	Liebermann-Storch-Morawski
LOI	Loss-on-ignition
MAIC	Mine Action Information Center
MRE	Mine risk education
MAG	Mines Advisory Group
NAMSA	NATO Maintenance and Supply Agency
NGO	Nongovernmental organization
NPA	Norwegian People's Aid
NMR	Nuclear magnetic resonance
RCAF	Royal Cambodian Armed Forces
RDX	Research Department Explosive
SEM	Scanning electron microscope
SERDP/ETSCP	Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program
SOM	Soil organic matter
TNT	Trinitrotoluene
UV	Ultraviolet
UXO	Unexploded ordnance
YR	'Yellow-red' (hue)
VI	Vulnerability index
WRA	Office of Weapons Removal and Abatement (U.S. Department of State)

Elements List

Al	Aluminum
Ag	Silver
B	Boron
Ba	Barium
Br	Bromine
C	Carbon
Ca	Calcium
Cd	Cadmium
Cl	Chlorine
Cr	Chromium
Cu	Copper
Fe	Iron
Hg	Mercury
K	Potassium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
Na	Sodium
Ni	Nickle
O	Oxygen
Pb	Lead
S	Sulfur
Sb	Antimony
Si	Silicon
Sn	Tin
Sr	Strontium
Zn	Zinc
Zr	Zirconium

1. Executive Summary

Most of the mines that currently threaten populations were manufactured more than 50 years ago and many have been in the ground for 30 years or more. Despite the inevitable and obvious deterioration, there has been very little research into the effects of aging on landmines.

In 2008, James Madison University (JMU), the Center for International Stabilization and Recovery (CISR), and C King Associates Ltd (CKA) began a study designed to understand the aging process and the range of implications for the various components of mine action. The two-and-a-half year study was funded by grants from the US Department of State, Bureau of Political-Military Affairs/Office of Weapons Removal and Abatement.

Methodology

The study involved the following four key elements:

1. **Field work.** The study team worked with demining partner organizations in Cambodia and Jordan, where a range of live mines were located, recovered, disassembled and examined in detail. Geo-referenced images were taken at every stage and soil samples were recovered from around each mine. Further data came from the Falkland Islands, where CKA was conducting similar work. Additional anecdotal information and images were gathered from several other mine-affected regions in which CKA had worked.
2. **Scientific analysis.** The Science departments at JMU conducted analysis of mine components in order to classify the materials and examine patterns of degradation. The soil samples were analyzed to identify relevant characteristics and look for correlations with the condition of mines.
3. **Literature review.** A literature review was undertaken to establish what work had already been conducted in this area, although little was found. Once the component materials had been identified, existing research supported observed common degradation effects.
4. **Predictive modeling.** Theoretical tools were developed in order to model the observed effects. Although basic at this stage, these have the potential to evolve into sophisticated models with which to predict the degradation process across a wide variety of mines.

Key findings

The study identified a broad range of significant findings, which include the following:

- Landmine aging is happening now; many mines already show a high degree of degradation.
- Aging has substantially altered the appearance of many mines. The pictures and models used for mine-risk education and deminer training are often inaccurate and misleading.
- Most mines are becoming non-functional, although the rate at which this occurs is dependent on a range of factors. Although some mines may become more dangerous as they deteriorate, this is rare.
- There are many ‘failure mechanisms,’ but most occur as vulnerable materials degrade.
- Penetration of the outer casing, exposing internal components to the environment, substantially accelerates the rate of deterioration and reduces the lifespan of the mine.
- A ‘vulnerability index’ (VI) for a mine can be determined from key component materials. This modeling allows the prediction of aging effects and extrapolation to similar mines.
- The likely lifespans of different mine types in a country can be made; however, far more data is required from the field to allow statisticians to develop reliable projections.

Conclusions

Analysis into the effects of aging on landmines is long overdue, but far more data is needed. The study has revealed implications for virtually every component of mine action; it is simply no longer acceptable to treat mines as though they were new.

At the strategic planning level, findings should contribute to the prioritization of tasks and allocation of resources, while policy-makers will need to consider the questions raised about mine lifespans and definitions. At the field level the findings have clear implications for the selection of equipment and techniques. MRE materials should reflect the appearance of mines as they are now, not as they were when new. Changing characteristics should be considered during research and development of new equipment.

It is clear that further work is needed to understand the aging process in more depth, and that more information is required in order to refine the VI and lifespan models. The participation of mine action organizations would contribute greatly to the gathering of data, much of which is currently lost. In return, a better understanding of the effects of

aging on mines has considerable potential to enhance mine action by making it safer and more cost-effective.

2. Introduction

2.1. Background to the problem

In 2008-2009, James Madison University, the Center for International Stabilization and Recovery, and C King Associates undertook a research project, “Scoping Study of the Effects of Aging on Landmines.”¹ It was established in this pilot research initiative that very little in the way of scientific evidence is documented regarding the effects of age and environment on landmines. This initial Scoping Study provided evidence through analysis of mine samples from the field that landmines are being demonstrably affected by age and environment in their ability to function as intended. Based on these first samples of landmines from Cambodia, it was also observed that at least some landmines are being neutralized² over time due to aging and climate.

A key outcome of the initial Scoping Study was the recognition that there are important questions we do not understand about landmines, aging and environment that will have implications for the future of landmine clearance, mine-risk education, detection, R&D and strategic planning. Rather than supplying answers, this initial research elicited an ever-widening array of questions, such as:

- What were the original compositions of the mine components?
- How do the compositions change as they deteriorate?
- What factors have caused deterioration?
- How localized can these factors be?
- How does deterioration lead to the inability of a mine to function?
- Are the effects relevant to similar materials in different mines?
- How do the environmental factors differ in other regions?
- To what extent can the effects be quantified or predicted?
- Can the effects be influenced (to accelerate failure, for example)?

At the conclusion of this initial Scoping Study, the research team recommended that the study of the effects of aging and environment on mines be continued in order to:

- Analyze the characteristics of key materials used in mines
- Research the causes of deterioration within these materials
- Examine the failure mechanisms within affected mines
- Broaden the range of mines within the study
- Broaden the regional and/or environmental scope of the study
- Investigate, where possible, anecdotal evidence of aging

¹ Available for public access at: http://maic.jmu.edu/aging/aging_intro.html.

² ‘Neutralization’ is an important concept discussed in greater detail within this report; see Annex J, section 3.3.

- Analyze findings to establish the implications for:
 - Program funding
 - Military operations
 - Mine-risk education
 - Field procedures
 - Equipment development

It was further recommended that future research to quantify the effects observed and to validate the findings should utilize the support of specialists (in disciplines such as chemistry, geology and physics) and the use of laboratory facilities.

This current report discusses follow-on research activities undertaken as an outgrowth of these recommendations. It describes the first phase findings of what is intended to be a scientific multi-phase, multi-year research effort to understand and exploit the impacts of age and environment on mines.

2.2. Funding and partnerships

“Study of the Effects of Aging on Landmines, Phase 2, Year 1,”³ was funded by United States Department of State, Bureau of Political-Military Affairs/Office of Weapons Removal and Abatement from 2009-2010.

The most recent phase of research described in this report was conducted by a team consisting of the James Madison University’s Center for International Stabilization and Recovery, Department of Chemistry, Department of Geology and Environmental Science, and C King Associates Ltd.

Other organizations, particularly Golden West Humanitarian Foundation, The HALO Trust, Jordan’s National Committee for Demining and Rehabilitation, the Jordanian Armed Forces, and Norwegian People’s Aid, contributed to the success of this study by providing field access, laboratory facilities and logistical support.

2.3. Project goal

The primary goal of the “Study of the Effects of Aging on Landmines, Phase 2, Year 1,” was to provide sound technical data on the effects of aging and environment on landmines, in order to better understand the degradation process and support an approach to decision-making within mine action.

2.4. Project objectives

Overall project objectives for the Study of the Effects of Aging on Landmines were to:

³ For Scoping Study results, see: http://maic.jmu.edu/aging/aging_intro.html.

- Collect mine and environmental field data for selected types of mines from previously studied hot/wet environment (Cambodia) and new hot/dry environment (Jordan)
- Conduct rigorous scientific analysis on components of identified mines in James Madison University laboratory settings using state-of-the-art materials-analysis and environmental-science technology
- Complete analysis based on research results and compile into project report, prioritization tool(s) for mine action, and Phase 2, Year 1 follow-on recommendations of research

The remainder of the report is divided into the following sections:

Section 3: Methodology

Section 4: Field Work and Findings

Section 5: Laboratory/Scientific Summary Findings

Section 6: Moving Beyond: Vulnerability Tools, Extrapolation, Final Analysis

Section 7: Conclusion and Recommendations

Annexes A-K

3. Methodology

This phase of Aging Study research required an iterative approach to analysis of the effects of age and environment on landmines. Because the subject is new and without precedent, an exploratory research approach was employed, which consisted of data collection and analysis within a framework of general questions and hypotheses about landmines, age and environment.

The final research methodology overview is as follows:

- Research plan and selection criteria finalized
- Landmines, data and soils collected from minefields within two countries
- Landmine samples broken down for observation and qualitative analysis in country
- Samples transported to James Madison University (USA) laboratories
- Scientific laboratory tests conducted for materials identification and characterization of mine parts and soils
- Literature reviews conducted based on materials characterization and soils identification
- Scientific data analysis completed and initial conclusions proposed
- Additional anecdotal field observation data incorporated into initial conclusions
- Comprehensive research-team analysis of combined field, laboratory and anecdotal observations, conducted and recorded
- Initial findings shared with field experts for feedback, and conclusions refined
- Final implications, recommendations and prototype models developed based on findings
- Findings and next steps reported to the wider humanitarian mine-action community to encourage further research and discussion on this topic

3.1. Selection criteria

3.1.1. Field locations and country data

The locations for the field work needed to include multiple mine-affected regions representing different environmental conditions, ideally a hot, wet environment and hot, dry environment typifying a majority of the world's minefields. The locations had to satisfy other requirements as well, including:

- Accessibility and permissive working environment, including entry into live minefields
- Adequate security (no ongoing conflict)
- The presence of cooperative demining organizations (ideally more than one)
- Availability of suitable target mines, showing aging effects

- Access to a facility suitable for the breakdown of live mines

It was decided that Cambodia (hot/wet) and Jordan (hot/dry) fulfilled these requirements. One additional consideration was that in both countries, mines have been laid over a period of roughly 30 years, allowing for generalized comparison of mine samples from both countries within that timeframe.

Additionally, major organizations involved in mine action in both locations had pledged support to the study. Specifically, the research team were provided access to minefields being cleared by HALO Trust (Cambodia) and Norwegian People's Aid (Jordan).

At the same time, one disadvantage of Cambodia in particular was that mines were laid unsystematically and without record over the 30 year period, making it impossible to confirm how long individual samples had been in the ground and thereby limiting highly scientific comparative analysis of aging between samples both within Cambodia and from Jordan.

After receiving permission from the United Kingdom, anecdotal data was incorporated into this study from the Falkland Islands. Mines broken down and analyzed during clearance operations in 2010 were included for comparative purposes. Notably, mines in the Falklands were also emplaced within a 30-year time frame.

Finally, additional data and field observations were selected for comparative purposes in this study when available, including some from Afghanistan.

3.1.2. Breakdown facilities in field

The major mine-action organizations typically do not have facilities for the breakdown of ammunition. However, Golden West Humanitarian Foundation has been operating an 'explosive harvesting' plant for several years in Cambodia, offering the following advantages:

- Purposefully built explosives-storage and -handling facility
- Licensed by regional authorities
- Specialist equipment for ammunition disassembly
- Staff familiar with ammunition
- Existing stocks of live mines

GWHF and its U.S.-government sponsors kindly agreed to allow the use of the harvesting plant, also providing a great deal of logistic and administrative support.

Additionally, the research team was granted access through Jordan's National Committee for Demining and Rehabilitation to an appropriate workshop facility. This workshop, operated by the Jordanian Armed Forces, provided for safe storage and disassembly of the sample landmines. Breakdown activities and analysis were led by Colin King of C. King Associates Ltd.

3.1.3. Selection of target mines

The study sought mine types that would offer the greatest insight into the effects of aging on characteristics and performance. However, achieving a sound basis for comparison meant including not only mines with vulnerable materials and mechanisms, but also those that were more resilient.

The reality is that, within the regions visited, the study was obliged to accept whatever mine types were available at the time. Partners among the demining organizations were extremely helpful, but the extent to which the work could be permitted to impact upon clearance operations was clearly limited. Leaving mines in the ground once they have been located has a number of safety, security and cost implications that had to be balanced with the objectives of the study.

However, the recovery team was extremely fortunate that a variety of mines was available, and that sufficient numbers meant that a degree of selection was also possible. In the end, the major limitation was the time required for the recovery and disassembly processes. Where there were sufficient numbers to permit a choice within a particular mine type, a selection was made to range from the best condition to the poorest, with as many intermediate samples as possible.

Anti-personnel mines were given a higher priority than anti-tank mines. There were three main reasons for this:

1. AP mines are present in larger numbers within affected communities, and are responsible for the majority of injuries.
2. AP and AT mines tend to share the same materials and fuzing mechanisms⁴.
3. AP mines are generally easier to transport and disassemble; they also have substantially smaller explosive charges.

In summary, there was something to learn from every type of mine, and almost every sample within that category. Mine types with common materials and mechanisms permit a degree of extrapolation to other mines with comparable characteristics, while additional samples (of the same type) showing similar degradation help to identify trends and build statistical significance. Mines with less common characteristics offer an insight into the properties of materials and mechanisms which, although rare, may be particularly significant where they do occur. In practice, almost every material and component is used, in some form, in different types of mines.

Detailed analysis of more than 15 types of mines⁵ has built a substantial body of evidence with application to at least four times that number. Examination of more mines, either

⁴ AT mines often use fuzes similar to those in AP mines, but with an additional measure to protect the mechanism and raise the operating pressure to an acceptable level (hundreds of kg rather than tens of kg).

⁵ Additional mines were examined in less detail, but limited availability or only partial disassembly restricted the data recovered from the analysis.

during a follow-on study or routine demining operations, will build on this foundation to create a valuable database of aging characteristics.

In Cambodia, mine samples were collected in the northeast section of the country along the K-5 belt at multiple HALO Trust sites. Initially, 18 mine samples were identified, with 16 ultimately transported for further disassembly and analysis (with soil).

- Russian PMD-6 (3 samples)
- Russian PMN (6 samples)
- Russian PMN-2 (1 sample)
- Chinese Type 72 (6 samples)

In Jordan, mine samples were collected in the north of the country along the Syrian border at various Norwegian People's Aid sites. Initially, 21 mine samples were identified, with 15 ultimately transported for further disassembly and analysis (with soil).

- US M14 (6 samples)
- US M15 (2 samples)
- US M19 (1 sample)
- Belgian M35 (4 samples)
- British Mk 2 (unable to move)
- British Mk 5 (2 samples)

3.1.4. Scientific research facilities

Research was also conducted in laboratory facilities within JMU.

Soils and environmental analysis associated with field landmine samples was conducted in James Madison University's Soils Lab, managed by Dr. Anthony Hartshorn (Assistant Professor, Soils) through the Department of Geology & Environmental Science.

Analysis of metal mine parts was conducted by Dr. Elizabeth A. Johnson (Assistant Professor) with help from Dr. Lance Kearns (Professor) through JMU's Department of Geology & Environmental Science and Center for Materials Science using the Scanning Electron Microscopy Laboratory.

Analysis of plastics, rubbers and metals from mine parts was conducted by Dr. Kevin W. Davies, employed during the time of this research at JMU in the Chemistry Department (Assistant Professor, Chemistry and Biochemistry).⁶ Dr. Davies also conducted field research in Cambodia in support of this phase of the Aging Study.

Research was coordinated by the Center for International Stabilization and Recovery at James Madison University, coordinated by Daniele Ressler and a research support team.

⁶ Dr. Davies is currently working at Florida Gulf Coast University, Department of Chemistry and Mathematics.

3.2. Field recovery of mines: sequence of events

Sample landmines were collected from Cambodia and Jordan. The initial process of recovery and research of the mines in the field followed this methodological sequence of events (these events are pictorially presented in *Annex A*):

- Arrival on site, also followed by orientation and safety briefing
- Review of objectives and formulation of mine recovery plan
- The team moves into the field, complete with PPE and medic
- A deminer confirms location of each mine and begins excavation
- The deminer ceases excavation as soon as the mine is visible
- The recovery team continues to uncover the mine with minimal disturbance
- A complete photographic record is made as the mine is uncovered
- The temperature of the ground near the mine is measured
- Soil from the ground in contact with the mine casing is recovered and labeled
- The mine is removed from the ground, disarmed and examined
- Every step of the process is recorded, along with the coordinates of the mine
- Recovered mines, complete with detonators, are packaged for transportation

3.2.2. *In-country workshop laboratory analysis of mines: sequence of events*

Once mine samples were collected from the field and ready for safe transportation, they were moved to workshop facilities for basic breakdown and analysis. The following sequence of events was typical for the analysis of mines recovered from the field. Notes and photographs were taken, as appropriate, throughout the process.

- Unpacking of mines and safety check
- Visual comparison and observations while in field condition
- Prioritization of mine samples for analysis
- Cleaning of external surfaces
- Assigning unique identifiers and labeling mines and components
- Complete disassembly:
 - By reversal of the manufacturer's production process, where possible, or
 - Using tools to cut into housings⁷
 - Including the removal of explosive charges.
- Cleaning of internal parts and surfaces
- Detailed examination of components
- Partial re-assembly, as appropriate, for mechanical testing
- Basic field material analysis, including:
 - Visual identification

⁷ Cutting was required where components were welded, bonded or otherwise permanently fixed, and when corrosion or deterioration prevented separation.

- Magnetic properties of metals
 - Chemical testing of rubbers and plastics
- Configuration of assemblies for explosive testing,⁸ comprising:
 - Selection of fuzing components
 - Assembly of firing mechanism
 - Placement in drop-test or pressing rig
 - Insertion of live detonator/booster
 - Conduct of the drop or pressing test
 - Recovery of components and examination of remnants
 - Review of video footage.
- Ignition testing,⁹ comprising:
 - Ignition of TNT block (complete with remnants of detonator)
 - Observation of burn and explosion of detonator
 - Bagging, labeling and recovery of components for laboratory analysis

3.3. JMU laboratory analysis of plastics and rubbers: sequence of events

3.3.1. *Properties analysis of rubbers, plastics and polymers*

A fast, inexpensive, and easy-to-utilize approach to identifying polymers and rubbers was used to analyze the non-metallic landmine components; this approach was based on work in other research contexts and modified by the research team to better handle the specific challenges posed by samples from aging landmines.¹⁰

The methodological sequence of events related to analysis of rubbers and plastics is as follows:

- Cataloging all samples, weighing, IDing, and documentation of external characteristics of mine sample parts
- Metallic and non-metallic (plastic, rubber) parts separated for different tests
- Samples from the mines selected to be used for analysis
- Physical properties tests conducted to generally classify and identify the materials in question, e.g.,:
 - Melts when touched with a hot needle/soldering iron?
 - Consistency to the touch (rubbery, foamy, etc.)?
 - Floats?

⁸ Conducted in Cambodia on PMN and Type 72 detonators.

⁹ Conducted in Cambodia on PMD-6 TNT blocks with detonator remnants still inside.

¹⁰ The tests based on physical properties could be heavily influenced by additives in the sample, and so they served to guide us in the identification but served primarily to augment the colorimetric tests. In the colorimetric tests, we anticipated a few difficulties in reaching a definitive identification due to the small sample sizes available and because the components had been degraded/contaminated over a long period. Despite these difficulties, these tests are a useful way to narrow down the possible identifications to 2-3 plastics or rubbers, which can then be distinguished by additional testing. It is worthy of note that these tests could be extremely field-portable, and may be useful for follow-up studies on-site even with the challenging experimental conditions one might expect in places like the fields of Cambodia or the deserts of Iraq.

- Burns? Smoke color/smell?
- Colorimetric tests (Burchfield and Liebermann-Storch-Morawski reactions) to further identify materials in question
- Nitric acid bath used to dissolve the organic compounds in the plastics and rubbers to determine the inorganic content
- Results of identified or inconclusive materials analysis for plastics and rubbers documented

3.3.2. *Fourier Transform Infrared Spectroscopy (FTIR)*

Additionally, Fourier Transform Infrared Spectroscopy (FTIR) was used on non-metallic components to verify the preliminary identifications from the tests above.¹¹ Two methods were used to measure the FTIR spectrum:

- Reflectance mode, shining infrared light at the surface; any light absorbed cannot be reflected, allowing the reflectance spectrum to give information analogous to shining the infrared light transmitted through the substance, but requiring almost no sample preparation.¹²
- Samples dissolved in a solvent (e.g., acetone), dripped into KBr salt crystals, and the salts dried then pressed under high pressures to form a pellet. (This is necessary because FTIR uses infrared light, which is absorbed by most substances, but not KBr.)¹³

3.4. Analysis of metals and corrosion: sequence of events

Metals parts from sample landmines were examined through Scanning Electron Microscopy (SEM) with Energy Dispersive X-Ray (EDX) microanalysis. An SEM-EDX instrument was used to take microscopic-level images of metallic components of sample mines in order to identify these materials.¹⁴ Data was collected in two ways: a few points of interest were ‘parked’ over and analyzed to give high-quality composition

¹¹ The basic principle behind FTIR is that different bonds in a substance vibrate at specific frequencies but not at others. Given the complexity of many chemicals (especially including plastics and rubbers) these peaks alone may not yield an identification, but coupled with a preliminary identification they can readily verify the identity of the substance, and occasionally give information about additives in that sample.

¹² Reflected mode often gives lower resolution spectra and may have very different intensities on the spectrum than other methods.

¹³ This method yields spectra that are more similar to those commonly in databases, books, and journals. Despite the different appearances of the spectra from these two methods, both yield similar peak positions when one considers the wave number (x-axis— this corresponds to the vibration frequency of a specific bond in the substance) and not the intensity. It is important to note that in these spectra, the ‘valleys’ are commonly referred to as the ‘peaks’—this is because the y-axis in is % transmittance or % reflectance mode, and we are interested in where the molecule absorbs at that wave number (i.e., less light reflected or transmitted).

¹⁴ In SEM-EDX, a beam of electrons is directed at the surface of interest. When the atoms on the surface are hit with an electron, the atom gives off an X-ray; different atoms give off different energy X-rays and by measuring the energies of the X-rays released, the composition of the surface can be determined. The instrument used can detect and quantitate atoms heavier than carbon that are present in atomic concentrations of 0.5% or greater.

measurements; or the beam was rastered across the surface, giving lower quality compositional measurements but allowing the research team to visualize where the various elements were present. These point analyses and element maps were archived in digital data sets, along with composited images.¹⁵

Analysis of cross-sectional area lost to corrosion, specifically for metal pins in sample mines, was then conducted to better understand the process of corrosion for this critical mine part.

The methodological sequence of events related to metal identification and corrosion analysis is as follows (see also a pictorial sequence of events in *Annex B*):

- Selected metal parts from sample mine are photographed
- Surface corrosion of metal parts is documented using binocular microscope
- Parts are sectioned using a slow-speed diamond saw
- Cut surface is polished with diamond paper to expose cross-section
- Cross section is photographed
- Cross-sectional area lost to corrosion (for pins) is quantified using Google Sketchup
- Samples are mounted on carbon-coated Scanning Electron Microscopy mounts
- Textures and qualitative compositions of metal parts and materials produced by corrosion are analyzed using the Scanning Electron Microscope at JMU
- Samples are archived in labeled boxes

3.5. Analysis of soils: sequence of events

During the field visit soil samples directly in contact with sample landmines were collected, labeled and packaged for transportation to James Madison University with a USDA Soils Permit. Once the soil samples were approved to enter the United States, they were transported to the JMU soils lab and the following methodological sequence of events related to soils identification and analysis occurred:

- Bag label information transferred to a spreadsheet and samples allowed to air-dry
- Samples given a unique ID (C1-C18, J1-J16)
- Samples sieved (<2 mm)
- Subsamples oven dried (to obtain oven-dry fraction for later conversion to units requiring oven dry soil weights)
- Subsamples treated with hydrogen peroxide to remove organic matter prior to textural analyses

¹⁵ The element maps and composited images show each element in a different color – each color has a separate intensity scale. As a result, these element maps should not be considered a quantitative picture of elemental compositions, but rather to visualize what physical features contain the same elements. This allows us to understand which elements appear in the corrosion layers versus the underlying metal. A detailed determination of the specific alloy types was not attempted in this work.

- Subsamples treated with sodium hexametaphosphate as a dispersant as part of textural analyses (% sand, silt, and clay)
- Subsamples ground with a mortar and pestle and shipped to Nebraska for total carbon, total nitrogen analyses
- Subsamples analyzed for pH and electrical conductivity (1:1 water)
- Subsamples sent to Nevada for total elemental analyses
- Subsamples microwaved and baked in a muffle furnace to determine loss-on-ignition (allowing estimation of soil organic matter)
- Subsamples assessed for hue, value, and chroma using Munsell color system
- Subsamples extracted with 1M NH₄Oac (ammonium acetate) and 1M KCl (potassium chloride) for determination of exchangeable base cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) as well as cation exchange capacity
- All samples archived in labeled boxes in a permanently locked room in Memorial Hall, JMU

3.6. Literature review conducted

A general literature review was conducted by the JMU research teams to examine empirical data related to common materials associated with landmines within the context of degradation and other effects of potential environmental characteristics and processes. It also reviewed literature related to soils analysis techniques that might inform landmine degradation and aging analysis. The full literature review is found in *Annex C*; only summary points are included here.

Examining the external components of landmines, which can impact how long a mine may resist degradation by outside elements, reveals that fire damage and weathering of plastics are two major considerations. Looking at the internal components of landmines, which can relate to how quickly and in what ways a mine is affected by environment once the casing is breached, shows that galvanic cells, explosive degradation and corrosion of metals are important. Literature linking research of materials, landmine degradation and environmental indicators or factors (soil, climate, etc.) that may allow predictive changes in landmine functionality was found, but very little research exists specifically examining aging in landmines.

3.6.1. *Fire damage and heat*

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. Many mine samples had evidence of exposure to fire, and this literature offers perspective on how that may be expected to alter the external body of the mine in particular, potentially leading to greater vulnerability (or conversely, less).

3.6.2. Weathering of plastics and rubber

On the whole, most research related to UV weathering was related to above-ground exposure, which may not be applicable to analysis for mines covered by foliage or soil, etc. However, UV degradation effects on some rubber was found to increase the polymers' overall tensile strength while decreasing its ability to stretch (i.e., increased rigidity). Thus, if something made with polymers requires a certain amount of flexibility to operate then this process will start to impede that flexibility and potentially, overall functionality. For some hard plastics color change is the main observable effect of UV.

3.6.3. Galvanic cells

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. Due to the complexity and concentration dependence, doing a specific study of the effect of galvanic cells may be useful in future aging landmines research.

3.6.4. Explosive degradation

Literature on explosive degradation did not present a strong comparative opportunity for current aging study landmine research, in part because little analysis was done relating to the project's sample mines and the functionality of their explosives. Literature found also focused on dissolving of explosive particles in an outdoor environment, with free-flowing water and over various surface areas; these are not the likely characteristics related to functionality of explosives within the landmine unit (i.e., explosive affected by stagnant water and a protected 'inner' environment).

Agitation of the explosive-water interface speeds up dissolution in most cases. There is relevant data pertaining to the effect of rotating, heating, surface area and vibration on the dissolution of various explosives. The effect of rotation was found to cause an increase in dissolution of all compounds. Increase in heat also increases the ability of chemicals to be dissolved. Surface area has the same increase as the rest with the exception of RDX, which has been found to be stable regardless of the surface area. The vibrational affect is similar to that of the rotation in that all the compounds had an increase in solubility. A comparison of different pH levels found that at low acidities there was not a distinguishable change in the dissolution rates.

3.6.5. Corrosion of metals

Metal corrosion can be characterized as the interaction of elemental metal plus water going to metal hydroxide and aqueous hydronium ion. When a metal cools, areas of chemical instability accrue, creating a site for accelerated decomposition in the metal. Research specific to stainless steel identifies how change in the composition affects the corrosion process; however, this covers only stainless steel and is analyzing modern

techniques for creating the stainless steel. If the metal specimens being examined are made with inferior techniques and metals, it can be assumed that this process will be accelerated. This, in combination with the galvanic cells, is expected to cause the majority of the degradation of a metal. Also, decomposition of metals is not the only degrading process—plating/deposition was observed in Phase 1's seized-up PMN strikers.

3.6.6. Literature related generally to the degradation of elements in the environment

While literature specific to landmine degradation is sparse, there are papers that relate generally to degradation of elements (found within landmines) in the environment (i.e., Fe, Mn). Features of soils are responsible for the corrosion of iron, which helps explain why metallic mines in Cambodia, but not Jordan, suffer extreme corrosion (soil aggressiveness can essentially be quantified, which would be a useful measure in future aging degradation research). Research points to the necessity of measuring redox potential in order to see what effect it has on landmine (especially iron-based) degradation. Additional literature touches on how clay-based, acidic soils are more aggressive (and therefore more likely to corrode metals).

3.6.7. Additional research and implications

Most research literature about emplaced landmines focuses on expensive methods to detect and remove landmines. While the need for alternative methods to removal is recognized, as well as the need for a multidisciplinary approach, very few research efforts seem to be currently applied outside the box of novel, for-profit landmine detection and removal R&D efforts.

Literature review has supported the potential equation developed in the current Aging Study research effort:

$$\text{LMR} = \text{VI} * \text{E} / \text{T} \text{ (Live Mine Risk} = [\text{Vulnerability Index} * \text{Environment}] / \text{Time}).^{16}$$

Literature review has also indicated that soil maps might provide an index of soil aggression, potentially one of the most important ingredients in the environmental factor portion of $\text{VI} * \text{E} / \text{T}$, along with water. It is anticipated that such mapping work can be useful in establishing soil traits such as pH, which will give future Aging Study researchers a better predictive model of soil aggressiveness.

To conclude, literature review supports both current Aging Study research efforts and provides promising future models and data sets for refined analysis of understanding and predicting the effects of time and environment on landmines. Additionally, as materials analysis and degradation principles of landmines over time and in different environments is refined, further literature will be found of use in specific industry sectors (e.g., studies of aging materials exposed to environments in engineering publications).

¹⁶ See Annex J, sections 4.1 and 5.3 for more discussion on this concept.

4. Field Work and Findings

4.1. Overall mine findings from Phase 2 field work

The mines examined in Cambodia were generally in much worse condition than those found in Jordan or the Falklands, with a substantial proportion being incapable of functioning. In contrast, most of the mines recovered in Jordan and the Falklands appeared to be in remarkably good condition and were clearly capable of operating.

One of the major problems encountered during the study was the difficulty in finding mines of the same type in different locations; this limited the opportunities for ‘like-for-like’ comparisons. The major exception here was the Russian PMN, where samples from Afghanistan were compared to those from Cambodia. The condition of the Afghan mines was significantly better, supporting the intuitive conclusion that—for this mine, at least—a wet climate and highly organic soil promotes faster deterioration.

There was clear evidence from all regions that water was the primary cause of deterioration, but it was surprising how many other contributing factors emerged. In some instances—particularly in Cambodia—mechanical damage and plant action had penetrated the mine casing, enabling water to enter sooner, or in larger quantities than might otherwise have been expected.

In Jordan, many mines were affected by fire,¹⁷ which damaged water-tight seals or created breaks in the casing. For those mines that avoided fire, the hot climate and intense sun in the high minefields of Jordan had done surprisingly little damage to the plastic mine casings. Most metal-cased mines were very well preserved by the Jordan climate, with some Second World War mines still functional.

Among the most resilient plastic-cased mines¹⁸ in the Falklands, the ingress of water was due mainly to ‘human error,’ where detonator plugs had not been tightened sufficiently. In mines that had been properly sealed, hardly any deterioration was evident.

One of the most important conclusions from the field was that the appearance of mines generally reflected their functionality. In other words, mines with noticeable external deterioration were often incapable of functioning, and vice versa.

¹⁷ Brush fires regularly sweep through the dry surface vegetation within mined areas; however, mines buried more than a few centimeters are unlikely to be affected.

¹⁸ Particularly the Italian SB-33 and SB-81, which have polycarbonate-based bodies.

4.2. Cambodia mines (see accompanying field images in *Annex D*)

4.2.1. *Russian PMD-6 anti-personnel mine summary of findings*

- The wooden case of every PMD-6 had rotted, with only small remnants found. Since the casing forms part of the initiation system (by pushing the retaining pin out to release the striker), these mines could no longer function as designed.
- The MUV-2 fuze components were intact, but were seized and had to be separated using force. The stab receptors were in poor condition and were probably not functional.
- The upper section of the aluminum detonator tube had corroded away, leaving a break of approximately 5-10 mm between the fuze and the main charge. This gap was filled with mud, which would probably have prevented the flash from the stab-receptor from initiating the detonator.
- Burning tests on two charges resulted in eventual detonation, indicating that the primary explosive within the detonator was still viable, and capable of initiating the main TNT charge.

4.2.2. *Russian PMD-6 conclusions*

- All of the PMD-6 mines examined showed multiple causes of failure, namely:
 - Absence of the casing as part of the initiation mechanism;
 - Seizure of mechanical fuze components;
 - Inactive stab-receptors (subject to confirmation);
 - Interruption of the initiation train.
- The combination of these effects would make it impossible for any of these mines to function as designed. Other PMD-6 mines buried in similar conditions for similar periods are also unlikely to function.
- The TNT charges are still hazardous, particularly since they contain embedded detonators with viable primary explosive. These could be initiated if set alight or subjected to substantial impact.

4.2.3. *Russian PMN anti-personnel mine summary of findings*

- The steel bands securing the rubber covers were badly rusted in all examples; many were at or near the point of failure. This is known to reduce the detection signature.
- Rubber covers had deteriorated and hardened; some, but not all, were breached. This does not prevent the mine from working, but does allow water into the fuze mechanism.
- The main effect of water inside the mine is to cause the springs to rust. The striker spring is most critical to failure; however, deterioration of the plunger spring could potentially lead to a decrease in operating pressure.

- As noted in the previous report, springs in contact with alloy strikers appear to deteriorate more quickly than those around steel strikers.
- Most strikers were in operational condition, but one had deteriorated badly and was seized into its channel. This would have caused the initiation mechanism to fail.
- TNT charges were in good condition and detonators appeared to be functional. Two detonator tests (using a PMN fuze mechanism in good condition) resulted in detonation.

4.2.4. Russian PMN conclusions

- All of the PMN mines examined in Cambodia showed significant deterioration, but some still appeared to be functional while others clearly were not.
- The most common cause of failure is deterioration of the striker spring, which begins when water enters the mine and eventually results in disintegration. Other likely causes of failure include:
 - Degradation and seizing of the striker;
 - Prevention of operation due to silt build up in cavities.
- Explosive components appear to outlive the fuze mechanism.
- These findings are consistent with those from the first phase of the study.

4.2.5. Russian PMN-2 anti-personnel mine summary of findings

- The rubber pressure plate covers were badly perished, with large sections missing. In several examples, the top edge of the plastic casing was also split. This damage would not prevent the mine from working, but does allow water and silt into the fuze mechanism.
- The main effect of water inside the mine is to cause the springs to rust. The striker spring and detonator slider spring are both critical to operation and their deterioration can cause failure.
- Deterioration of the plunger springs could potentially lead to a decrease in operating pressure, but appears to be offset by seizing of the plunger itself.
- In every PMN-2 examined, the striker was seized into its channel; this appears to be caused by a build-up of corrosion, leading to expansion beneath the metallic plating.¹⁹
- In several examples, the mild steel firing pin (which is inset into the end of the striker) had rusted away completely, leaving the striker with a flat end.
- In all examples, the explosive charges (RDX/TNT) and boosters were in good condition and detonators appeared to be functional. However, the detonator is held out of line until the mine is actuated, and relies on the slider spring to bring it into line.

¹⁹ Some PMN-2 mines examined for a separate study have stainless steel strikers, which may be more resilient.

4.2.6. Russian PMN-2 conclusions

- All of the PMN-2 mines examined showed significant deterioration and none appeared to be capable of functioning.
- The most common cause of failure is seizing of the striker into its channel. However, some mines showed multiple points of failure, including:
 - Absence of the firing pin;
 - Seizure of the detonator slider and spring;
 - Seizure of the plunger.
- Explosive components appear to be stable and functional.
- These findings are consistent with those from the first phase of the study.

4.2.7. Chinese Type 72 anti-personnel mine summary of findings

- The rubber pressure plate cover was badly perished or absent in all of the mines examined. In every case, this had allowed water and soil to penetrate the mine body.
- Without the smooth green rubber cover, the appearance of aged Type 72 mines is quite different, and may not be recognizable to people who have only seen it in new condition.
- The primary effect of water inside the mine is to rust the mild steel firing pin. Initially, this causes the tip to become rounded and therefore shorter, which makes it far less likely to fire the igniter.
- The likelihood of initiation continues to fall as the mass of steel within the firing pin decreases further. This, combined with rusting of the helical arming spring, may also make the mine difficult or impossible to locate using a metal detector.
- Most of the Type 72 mines examined had fuzes that were already actuated (shown primarily by the inversion of the Belleville spring), but the mines had not detonated.
- Most explosive components remained in reasonable condition and appeared to be functional. However, some of the stab-sensitive igniters were no longer operational.

4.2.8. Chinese Type 72 conclusions

- Breaching of the thin rubber cover means that all Type 72s examined had significant levels of deterioration. However, some still appeared to be capable of functioning.
- The most common cause of failure is rusting of the firing pin. Degradation of the igniter may also cause failure, particularly in conjunction with a short, rounded firing pin.
- With the rubber cover missing, the mine can be difficult to recognize; this has important implications for mine risk education and deminer training.

- Older mines with minimal metallic content may require alternative means of detection.
- A complete explosive train (detonator, booster and main charge) may remain even when the fuze is non-functional. This means the mine is still hazardous.
- These findings are consistent with those from the first phase of the study.

4.3. Jordan mines (see accompanying field images in *Annex E*)

4.3.1. US M14 anti-personnel mine summary of findings

- After long-term exposure to hot conditions and bright sunlight, the M14 plastic casings showed few signs of deterioration, although the color had faded in some places.
- The stab-sensitive detonators and main explosive charges appeared to be in good condition and functional, with only slight superficial degradation.
- The material used for the Belleville spring appears to be highly resistant to deterioration.
- The mild steel firing pins had rusted to varying degrees, though most of the corrosion appeared to be superficial and unlikely to affect performance.

4.3.2. US M14 conclusions

- The bonded casing and rubber seals have permitted very little water to enter these mines. The Belleville spring, detonator and main charge have also proved resilient.
- The firing pin is probably the most vulnerable component, yet even these were relatively unaffected.
- The mines examined were probably capable of functioning as intended and, given the slow rate of deterioration, could be expected to remain so for many more years.

4.3.3. US M15 anti-personnel mine summary of findings

- The M15 mines were in good condition externally, with only superficial rust.
- Rust was confined mainly to the side of the mine, but had not penetrated the casing. Very little rust was visible on the top surface or base, other than the wire carrying handle.
- The steel fuze cap could not be unscrewed from the central well of the pressure plate using the available resources. Although little corrosion was visible, both assemblies are steel and had rusted together enough to prevent movement.

4.3.4. *US M15 conclusions*

- Examination of the internal components could not be conducted; however, based on the external condition, it is highly likely that the fuzes were in good condition and that the mines were fully functional.
- There is no evidence that water had penetrated the casings of these mines. Based on the rate of degradation seen here, these mines could remain intact for many more years.

4.3.4. *US M19 anti-tank mine summary of findings*

- The M19 mines casings were in excellent condition, with no visible deterioration.
- Rubber seals between the fuze assembly and body had hardened, but there was no indication that water had penetrated the mines.
- All explosive components appeared to be in good condition and fully functional.
- The main Belleville spring, responsible for maintaining an adequate operating pressure, showed no sign of deterioration. The small firing Belleville spring was also unaffected.
- The firing pin in the M19 is stainless steel and therefore highly resistant to corrosion.

4.3.6. *US M19 conclusions*

- The fiberglass used in the M19 casing appears to be virtually unaffected by age.
- Rubber seals are likely to fail gradually over coming years.
- The fuze assembly and detonator are both well protected and resilient.
- Water entering the mine body may take a long time to have any significant effect.
- M19 mines are likely to remain functional for many years to come.

4.3.7. *Belgian M35 anti-personnel mine summary of findings*

- Of the four M35 mines examined, three appeared to be functional.
- The mine (No. 1) that showed the greatest deterioration was protruding from the ground.
- Mine No. 1 had a distorted casing and a damaged fuze which had permitted the ingress of water. Bulged M35 mines are also seen in parts of Africa.
- Despite being misshapen, all of the plastic casings maintained their integrity.
- The explosive charges were crumbly, but it is not known whether this would affect performance.
- Most detonator and igniter capsules showed surface degradation, but appeared functional.

- The spring striker wires were functional in most mines. Both wires in mine No.1 were heavily corroded due to the ingress of water; this would have caused the fuze to fail.

4.3.8. *Belgian M35 conclusions*

- Buried M35 mines could remain functional for many years to come.
- Mines on or near the surface may be damaged by brush fires in Jordan.
- Once water has penetrated the casing, the most likely failure mechanism is the deterioration of striker wires, detonator and igniters.

4.3.9. *British Mk 2 anti-personnel mine summary of findings*

- The fly-off lever was heavily rusted, posing a potential danger that, with little stimulus, it might release the striker and detonate the mine.
- Mk 2 mines are therefore considered too unpredictable to examine in detail, however:
 - Trip wires were absent, so the mines could not function as designed.
 - All visible external steel components were heavily rusted.
 - The condition of strikers and springs could not be established but, based on findings from the Mk 5 mines, might still be functional.

4.3.10. *British Mk 2 conclusions*

- Although incapable of functioning as intended by tripwire actuation, these mines may still pose a significant threat if disturbed.
- The most likely failure mechanism is that the strikers, springs and retainers seize together to prevent operation of the fuzing mechanism.

4.3.11. *British Mk 5 anti-tank mine summary of findings*

- The external steel surfaces were rusted, but not excessively.
- The alloy fuze body showed only slight deterioration.
- The simple fuze mechanism (spring-loaded striker retained by a shear pin) was functional.
- The booster charge was dry and in perfect condition, suggesting that the detonator assembly was probably in a similar condition.
- The main explosive charge appeared to have melted and recrystallized, resulting in expansion.
- Expansion of the main charge had created a friable mass and forced the base plate off the mine.

4.3.12. *British Mk 5 conclusions*

- Unlike many other mines showing the effects of aging, the Mk 5s appeared to have fully functional fuzes.
- It is unlikely that the main charges would be capable of sustaining complete detonation.

4.4. Falkland Islands mines (see accompanying field images in *Annex F*)

4.4.1. *Spanish P4B anti-personnel mine summary of findings*

- Most of the P4B mines examined appeared to be fully functional.
- Deterioration of the plastic casings has begun, but—in most instances—is progressing at a far slower rate than expected. Most mines have retained their structural integrity.
- The ingress of water into the fuze assembly has caused only minor deterioration of the striker springs. This will not significantly affect the detection signature or the mine's ability to function.
- The ingress of water into the detonator assembly may render the mine inoperative; this would need to be confirmed by testing.
- The lead foil was present in all but one of the mines examined. The manner in which the foil splits (when the fuze assembly is fitted) may affect the detection characteristics of the mine. Determining this would require additional trials.
- The TNT HE content is stable and well preserved.

4.4.2. *Spanish P4B conclusions*

- The plastic used in the P4B casing has proven more resilient than expected.
- The mines are best preserved when buried, since the plastic becomes brittle when exposed to sunlight.
- The P4B fuze may be capable of functioning even if the fuze spring has rusted away.
- The detonator is prone to becoming wet, and this is likely to be the primary failure mechanism in the long term.

4.4.3. *Italian SB-33 anti-personnel mine summary of findings*

- Most of the SB-33 mines examined appeared to be fully functional.
- The rubber pressure plates were distorted where the material appeared to have softened; this probably indicates the beginning of degradation that would eventually lead to failure.
- Deterioration of the rigid mine casings was minimal and all of the mines examined retained their structural integrity.

- Minor dampness inside the mines has caused only minor deterioration of the striker springs. This will not significantly affect the detection signature or the mine's ability to function.
- Degradation of the detonator assembly, due to dampness, may render the mine inoperative; this would need to be confirmed by testing.
- The HE charges are well preserved, despite some being cracked.
- Where water had penetrated a mine, the striker spring and detonator capsule showed substantial deterioration; this would almost certainly have prevented it from functioning. In the long term, this is what could be expected to happen to all SB-33 mines in the Falklands.

4.4.4. Italian SB-33 conclusions

- The SB-33 is extremely resistant to wet conditions.
- The weakest points are the rubber cover section of the casing and the O-ring sealing the detonator plug.
- Once water has penetrated, both the detonator and the fuze spring are vulnerable.
- The rubber cover of the SB-33 may prove vulnerable to hot, dry and bright conditions.

4.4.5. Italian SB-81 anti-tank mine summary of findings

- Most of the SB-81 mines examined appeared to be fully functional.
- The mine casings showed no signs of deterioration; however, prolonged exposure to sunlight is likely to cause degradation that would eventually lead to failure.
- Minor dampness inside the mines has caused only superficial rusting of the striker springs. This will not significantly affect the detection signature or the mine's ability to function.
- Degradation of the detonator assembly, due to dampness, had occurred in some mines and might render the mine inoperative; this would need to be confirmed by testing.
- The HE main charges and boosters were in good condition.

4.4.6. Italian SB-81 Conclusions

- Like the SB-33, the SB-81 is extremely resistant to wet conditions.
- Once water has penetrated, both the detonator and the fuze spring are vulnerable.
- The pressure plate is likely to be vulnerable to hot, dry and bright condition.²⁰

²⁰ Other Italian mines with similar structures (such as the TC/6, VS-1.6 and VS-2.2) tend to fail in hot climates when the pressure plate hardens and cracks develop in the thin shoulder. This prevents the pneumatic fuze system from working.

5. Laboratory/Scientific Summary Findings

5.1. Materials Analysis (Full reports in *Annex G* and *Annex H*)

5.1.1. Russian PMD-6 (Cambodia)

Russian PMD-6 samples were found in Cambodia. In this study, only the explosive and detonators were found intact in the field for PMD-6 samples. The explosive was tested for viability by igniting a portion. The TNT charge appeared to remain viable. However, all other parts of the triggering system appeared to be non-functional.

The firing pin had rusted into place in the fuze, requiring considerable pulling force to remove. In order to access the interior components of these fuzes, the housing was cut in half. The interior metal components were rusted, but overall, most seemed to remain operational (e.g., springs rusted but remained stiff). Infiltration of roots, deposition in striker channel, and dislodgement of the fuze from the TNT block are examples of the systemic causes of PMD-6 mine failure.

Only one rubber component was recovered (a rubber cap that sits near the firing pin); this rubber was quite brittle. Unfortunately, this sample was too limited/degraded for identification.

5.1.2. Russian PMN (Cambodia)

The Russian PMN was extensively researched in the JMU laboratory using samples from Cambodia. Some of the findings for mine body parts are listed below:

Cover: Styrene butadiene rubber, with SiO₂ as an additive; the cover is held in place by a metal band.

Casing: Bakelite exterior with rigid rubber housing.

Spring: Comprised of an iron core, with a tin protective covering. It appears that during the manufacturing process, the iron spring was dipped into a bath of molten tin (and sulfur and copper may also have added to this bath).

Striker: Striker tip was found to be coated with a thin zinc layer (32% Zn, 68% Fe) over an iron underlayer (98% Fe, 2% Zn). The central cylinder (77% Fe, 23% Zn after cleaning) and spring guide (94% Fe, 6% Zn after cleaning, with high Zn/Mg areas) both had a thin layer of zinc on the surface and were primarily iron underneath.

The PMN has an exterior body made of Bakelite, a highly durable plastic that appears to be largely unaffected by environmental processes as observed in this study. The top rubber covers of PMN were made from a styrene butadiene rubber with SiO₂ as an additive, which is a combination known to be durable and is found in a variety of applications, including truck tires. These rubber components were typically found without significant damage or decomposition in the samples.

However, in Cambodia samples the metal band holding the cover in place frequently displayed corrosion, which in some cases led to the band's being broken. And while the striker assemblies examined during research were deemed likely to function as intended, it was observed that failure to function as intended amongst PMN mines appear to be most commonly attributable to metal component failures. Samples examined had spring coils that had collapsed/broken, probably due to some sort of metal occlusion in the tin coating over the steel core.

5.1.3. Russian PMN-2 (Cambodia)

The Russian PMN-2 was extensively researched in the JMU laboratory using samples from Cambodia. Some of the findings for mine body parts are listed below:

Cover: Rubber cover over the cross-shaped pressure plate; the rubber is a chlorine-containing rubber, ~50% of the mass is SiO₂ from a quartz additive.

Casing: Rigid plastic, a poly(phenylene) oxide (PPO) housing.

Spring: Comprised of an iron core, with a tin protective covering. It appears that during the manufacturing process, the iron spring was dipped into a bath of molten tin.

Striker: The PMN-2 striker tip was either primarily composed of zinc (93% Zn, 2% Cr, 2% Ni, 2% Fe), or had such a thick coating of this metal that the subsurface would have no exposure to its environment. The center portion of the striker had a nickel-phosphorous coating (86% Ni, 14% P) over an aluminum core (91% Al, 5% Cu).

The protective coating on some strikers has separated from the aluminum underneath, and the sampled metallic flakes are made of this same nickel-phosphorous material. The spring guide is also coated with nickel-phosphorous over an aluminum core; significant deposits of iron were also found in this area. No element maps were acquired for this striker. The nickel-phosphorous coating falls under the category of 'high phosphorous' and was probably deposited via the electroplating or 'electroless' plating processes.

Inside, numerous metal components had failed (e.g., the striker had expanded/mushroomed and seized in place in the stepped window, the spring attached to the detonator had failed, and the striker spring had begun to collapse—all in one single mine sample).

In the PMN-2, the failure of the rubbers probably has strongly contributed to the sequential breakdown process this mine experienced; however, the top rubber covers obtained from the field were significantly deteriorated (visually this appears to be a result of fire damage) and as a result, complete materials identification remains elusive.

5.1.4. Chinese Type 72 (Cambodia)

The Chinese Type 72 was extensively researched in the JMU laboratory using samples from Cambodia. Some of the findings for mine body parts are listed below:

Cover: EPDM rubber with an SiO₂ filler (subtype indeterminate).

Casing: Polyurethane plastic.

Firing pin: Fe coated with either an Sn or Sn-Sb alloy. Other trace elements include Hg, Mo, S, Si, Cl and K.

Center of pin: Fe metal with minor Sn, Sb, and trace O, S, Cl.

Outer edge of pin: Sn and Sb metal alloy and oxide, Hg (explosive residue), with minor Mo and trace Fe.

Casing at base of pin: Cu-Ni metal alloy with Sb coating, minor Fe oxide, S, Cl, K, B.

O-Ring: Polyurethane rubber.

Belleville spring: Layered polymer/fiber disk.

Interestingly, the rubber samples nearly all showed signs of fire damage on the mine. It cannot be determined if the rubber survived *despite* or *because of* the fire damage (perhaps a vulcanization effect?) but this question might be worth further consideration. The exterior casing of the mine was found to be a polyurethane plastic, and even with obvious signs of wildfire damage, the case was consistently intact.

5.1.5. Jordan mine samples materials analysis

Due to both project time constraints and prioritization of resources, the approach to materials analysis of Jordan mine samples differed from the Cambodia mine samples. While Cambodia mine samples were highly degraded and therefore warranted detailed materials analysis, the Jordan mine samples were significantly less degraded so the focus was on targeted parts in the mine samples that had evidence of degradation or represent likely weak points for future degradation.

The US M19 and Belgian M35 had seal components that appear to be a likely weak point for degradation resulting in entry of water, sand or soil into the internal mechanism; therefore these were analyzed.

US M19

O-ring: Identified in initial tests as silicon; however, this could be due to the large amount of quartz-style additive and requires additional testing.

Case: Polyurethane.

Belgian M35

Seal: Identified in initial tests as silicon; however, this could be due to the large amount of quartz-style additive and requires additional testing.

Black Rubber: Most likely PO but could also be TPO.

Additionally, in-depth striker pins materials analysis was conducted for sample mines from Jordan: the US M14 and M19.

US M14: Made of Fe metal and coated with a thin layer of non-corroding metal consisting of Cd metal.

US M19: Made of Fe metal and coated with a thin layer of non-corroding metal consisting of Cd metal.

5.1.6. *Metal materials analysis discussion*

The metal firing pins in the research mine samples were of particular interest because these mine components often have a critical role in a mine's ability to function as intended (or not). Accordingly, targeted analysis was done on select pins to better understand the process of degradation witnessed in samples (see ***Annex H*** for detailed discussion).

Analysis of these metal components led to the observation that if groundwater or rainwater (which has perhaps also picked up chemical constituents from the explosives within the landmine or from the environment) penetrates the mine casing and breaches the protective coating on the surface of the firing pin, an Fe metal pin will corrode to produce Fe oxide (rust).

Upon corrosion, the shape of the firing pin changes from a longer, conical shape to a blunter, shorter shape. The most severely corroded firing pin has no Fe metal remaining and is a mass of Fe oxide (rust) material, with no point remaining.

Most pins showed minimal loss of Fe metal in the cross-section examination. This suggests that the protective metal coating on the firing pins is often effective at protecting the pin from degradation. Once the coating is breached, however, a water-rich environment will rapidly degrade the Fe metal pin, affecting both shape and strength of the pin over time.

The firing pin is unlikely to be the first component to fail in the Type 72, M14 or M19 landmines since it is housed internally, but degradation of a firing pin may be a good indicator that a mine is potentially less likely to function as intended. Almost all firing pins from deployed landmines with show corrosion on the surface. The shape of the firing pin is one indicator of how far corrosion had progressed; quickly slicing or cutting the pin open will reveal how much original metal remains.

If 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.

5.2. Soil analysis (full report in *Annex I*)

Initially, 33 soil samples were collected for research from minefields in Cambodia and Jordan; however only 26 intact soil-landmine sample pairs were transported to James Madison University because some mines were deemed too high risk to move or study further or were unable to be safely defuzed.

Conceptually, the soils analysis research team at JMU used a process-based approach to examining the relationship between environment (represented by soils) and landmine degradation.

Soil samples were all analyzed for soil pH, electrical conductivity, soil texture, soil colors, soil organic matter, total carbon and total nitrogen, base saturation, major and trace elements. Besides properties analysis of the soil samples, an effort was made to conduct specific calculations combining soil property characteristics with field data identifying mine samples as likely to function as intended, not function as intended, or unknown. This represented a rough level of degradation activity.

5.2.1. Soils properties identification

In general, consistent with the soil organic matter trends, Cambodia soils were finer-textured (17% sand) than Jordan soils (35% sand). Jordan soils contained twice as much silt as Cambodia soils, consistent with the climate and proximity to loess-generating areas. The greater clay content of the Cambodia soils is consistent with prolonged chemical weathering under a hot and moist climate. These textural differences led, in turn, to nearly 4x-higher estimated hydraulic conductivities (the rapidity with which water can move through soils) for Jordan soils versus Cambodia soils. Soil electrical conductivities were similar.

In contrast with the Cambodia soils, where we observed some large differences in elemental chemistry between samples, most Jordan soils were quite comparable.

As is typical for soils, the most common element was silica, or SiO_2 ; SiO_2 is found in quartz, which is an important component of sand. The median SiO_2 concentration was 60% in Cambodia soils, slightly greater than the median concentration of 47% for Jordan soils. The next three most common soil ‘components’ soils were ‘loss-on-ignition’ (LOI, obtained by ashing soils at 1000°C for 1 hr.), aluminum (Al_2O_3) and iron (Fe_2O_3). The greater proportion of SiO_2 , Al_2O_3 and Fe_2O_3 is consistent with the higher clay content, while the greater proportion of the two principal ‘base’ cations, Ca and Mg, is consistent with dust-influenced, arid ecosystems.

While the soil carbon values were found to be comparable between Cambodia and Jordan samples, soil nitrogen values were not. Carbon-to-nitrogen ratios (C:N) indicate that the Jordan C:N were much higher than the Cambodia C:N. In fact, nitrogen in Jordan soils averaged 0.17%, about 36% less than Cambodia soils (0.27%). However, though 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. More research is needed to better determine whether C:N ratios are a critical part of landmine aging.

Of potentially greater interest for the purposes of quantifying landmine aging are landmine constituents such as tin (Sn), particularly since Sn values showed some of the

greatest ranges across all 50 constituents. These results suggest that corrosion of landmines could be associated with ‘leakage’ of Sn into the surrounding soil. Tin, therefore, might be useful in chemically ‘fingerprinting’ aging landmines since one consequence of the corrosion of landmines will be the release into the surrounding soil of ‘weathering products’ such as tin. It is important to note, however, that the relatively small sample size precludes broader generalizations.

This finding illustrates well an important outcome of this research. The Jordan results fall short of being an adequate test of the tin-leakage finding because even if some tin leakage had been associated with corrosion of the M14 landmines, the sandier textures (only ~31% clay) of the Jordan soils (versus ~60% clay for Cambodia soils) could have resulted in greater leaching of any ‘leaked’ tin. Future work should target material properties associated with landmines distributed across gradients of potential leaching. The most accessible of these gradients would be catenas, or hillslopes, where the same landmines can be found at crests (relatively dry) and at toeslopes (relatively wet).

5.2.2. Macro-analysis of soils in comparison to mine-sample functionality

Analyses based on soil properties compared with estimated mine functionality suggest an important interaction between country or climate and soil properties. The two non-functioning Jordan landmines (M14 and M35) had higher soil organic matter and slightly higher EC, whereas the non-functioning Cambodia landmine (PMN) had lower soil organic matter and EC; although in all cases, the variance within a specific landmine category was greater than the difference between functioning and non-functioning landmines. Only minor differences were noted in pH between functioning and non-functioning landmines.

For two of these three mine types, landmines that were determined to no longer function as intended were associated with more acidic soils, although the largest average difference was only 0.5 pH units. Additional analysis indicated that soil organic matter levels were higher in soils surrounding non-functioning landmines and pH levels were lower, although EC values generally overlapped for soils surrounding functioning and non-functioning landmines.

Unfortunately, no landmines complete with accompanying soil were encountered in both countries during this phase of research.²¹ Having overlapping, same landmine types would have helped in the interpretation of factors likely to influence landmine aging, the research team concluded.

5.2.3. Implications

²¹ In the previous Scoping Study as well in secondary support research conducted in the Falkland Islands and other places, same landmine types (e.g., PMN) were found in more than one of the Aging Study’s overall countries of research and therefore allowed some comparison of degradation in different environments; however, these earlier-studied and/or anecdotal samples had no soil collected with them and therefore could not be included for the Phase 2 in-depth soils-analysis research.

Because no comparisons of the same landmine deployed for different intervals of time in the same soil, nor the same landmine deployed for identical intervals of time across different soils, were available, our initial investigation of the soil properties most likely to predict the trajectory of ‘landmine aging’ has failed to zero in on a single ‘most promising’ soil property meriting further study.

The technical research team’s field assessments of landmine condition and likelihood of functioning as intended generally tracked the vulnerability index values developed during this phase of the Aging Study by the research team. This comparison suggests field assessments may provide a robust means of categorizing landmine aging, although much greater resolution of vulnerability x environmental interactions—as these interactions affect landmine aging and degradation—might be possible through sampling strategies that maximize a gradient approach to landmine aging.

The scope of current research on aging effects on landmines was limited, and ultimately the research team faced the problem of not being able to conduct research techniques that allowed a comparison of identical mines deployed for identical durations into:

- soils representing a toposequence (same macroclimate, same biota, same parent rock, but different parts of a hillslope or catena: crest, shoulder, sideslope, footslope, toeslope);
- soils representing a climosequence (same biota, same rock, same catena position, but different macroclimate zones); or
- soils representing a lithosequence (same macroclimate, same biota, same catena position, but different parent rock).

Although the research team was able to analyze and characterize soil samples from Cambodia and Jordan, and hypothesize about effects of environmental characteristics on the sample mines, the small number of same mine types did not allow comparative techniques that might have been able to isolate critical factors affecting landmines within an environment with scientific confidence.

Future research should include some of the following:

- Greater number of matched soil/landmine pairs (functioning and not functioning)
- Strategic expansion of locations for comparative advantage
- Increased, strategic collection of global field data
- Development of an Aging Landmines Data Repository for data collection and analysis.

6. Moving Beyond: Vulnerability Tools, Extrapolation and Final Analysis

6.1. Summary of report on models (full report found in *Annex J*)

6.1.1. *Development of a prioritization tool*

One of the objectives of the study was to develop a working framework or tool to assist WRA with the prioritization of area clearance. The study approached the requirement from two associated perspectives:

- The likely vulnerability of different mine types to the effects of aging
- The likely life span of those mine types under different conditions.

In both cases the starting point was the development of a simple model of aging affects on landmines and their components. It is important to emphasize that the aging models are not in themselves the tools that may be used by policy makers and planners. The models are, at this stage, simply a mechanism to help identify and understand the different factors associated with aging processes and to establish which factors are likely to be of the greatest significance. Additional detail about the development and form of the aging models is provided in (*Annex J*).

It was not feasible to develop a universal model of landmine aging which could be applicable to all types. Instead, for the purposes of this study a single mine type, the PMN, was selected on the basis that is both relatively simple to describe and found in large numbers in many affected countries. In due course adapted models could be developed for other specific or generic mine types.

The aging models started from the development of an influence diagram, which captures the various factors of significance and identifies the likely relationships between them. The model includes a basic description of the working components and sequence of events within the mine and then identifies external environmental factors which can be expected to have an influence on aging processes.

6.2. Prioritization and planning tools

The modeling process yielded two tools which could be used by planners and policy makers to support decision-making.

- **Vulnerability Index (VI) tables** allow users to compare different mine types to see which are most likely to degrade first. VI tables assess different mine types against a number of key indicators of vulnerability to aging. The tables allow planners to form an initial opinion on which types of mines are most likely to be degrading due to aging and, conversely, those which are likely to remain hazardous for the longest periods.

- **Mine lifespan charts** reflect a statistical assessment of the effects of aging on a population of mines. In much the same way that statisticians look at mortality rates in a human population, so it is possible to consider probable lifespans of landmines. The population can be specific to one type of mine or to a range of mine types found in a country or region. The initial analysis is based upon the assumption that mines within a population will fail along a normal probability distribution; that is, a small number of mines will fail relatively soon after laying, most will fail around some typical average lifespan and a few will remain hazardous for an unusually long period.

Vulnerability Index tables are intended to help operational planners to understand the susceptibility of different mine types to aging processes and so identify which mine types are likely to remain hazardous for longer.

Mine lifespan charts are primarily for higher level decision makers interested in understanding the longer term duration of mine presence in a country, and the significance of that presence both as a hazard and in terms of compliance with international conventions.

6.2.1. Vulnerability Index (VI) tables for landmine aging study materials and mines

The current phase of research began to rigorously identify the importance of individual mine components on the firing train and, thus, the ability of a mine to function in the way intended. Taking it a step further, to understand how a mine's 'out-of-box' functionality is impacted when any one component changes, the team coupled materials identification with each mine component. Using field observations of specific mines, the team developed the Vulnerability Index concept, in which major components of mines are listed and the known or suspected material(s) of that mine component are identified.

6.2.1.1. Material vulnerability ranking

Materials were then ranked according to 'resilience' to degradation, based on known chemical and materials science principles and research findings (**Table 1**). Within JMU, the Chemistry Department research team began scientifically identifying materials from sample mines and providing data on known or potential degradation processes (*see Annex G, H*). **Table 1** shows the most common non-explosive materials used in mines, ranked from the least vulnerable (such as composites and stainless steel) to the most vulnerable (such as rubber and wood). Since the exposure of surface area is a critical factor, the thickness of some materials is also taken into account. Each material listed in **Table 1** has then been allocated an abbreviation for convenience.

6.2.1.2. Component vulnerability index

There are two categories of mine component that are significant for the effects of aging; these are:

- Components critical to operation;

- Components critical to the integrity of the mine.

Components critical to operation will normally include the major elements of the fuzing system and of the explosive train. Removal or non-functioning of one of these components will normally render the mine incapable of functioning as intended.

Components critical to the integrity of the mine normally include the casing, along with assemblies (such as covers and plugs) that seal the casing.

Some components may fall into both categories, such as the casing of a box mine, which also provides the means of fuze actuation.

Not all of the components that fall into the above categories need be considered. This is because some are inherently less vulnerable than others. For example, many mines contain a booster that is critical to correct function; however, the booster is invariably composed of resilient high explosive and is located in a protected position. Field observation and common sense dictates that the initiator or main charge will fail before the booster. Similar principles apply to other components, such as sealing plugs.

Table 2 lists the most significant components, along with the materials normally used, and allocates them a rating from 1 (least vulnerable) to 5 (most vulnerable), per **Table 1**.

6.2.1.3. Vulnerability of mines

Table 3 shows mines examined during the study and rates their critical components according to the contents of **Tables 1** and **2**. The total of the various Component Vulnerability Indexes yields a **Vulnerability Index (VI)** for each type of mine. The higher the VI, the more prone to degradation as it ages; the lower the figure, the more resilient the mine is likely to be. For example, the PMN's casing is identified as highly resistant to degradation (1), but its rubber cover is relatively more vulnerable to degradation effects (4); the PMN's total VI was calculated as 19, out of a possible score of 35.

The VI only accounts for the vulnerability of the materials within the mine; however a number of other factors may contribute to its degradation. These include the degree to which it is watertight, the tightness of internal tolerances and its position (i.e., above-ground, flush with the surface or buried). These additional factors can be used to weight the VI in order to make a more realistic assessment of the aging effects.

6.2.1.4. Mine comparisons

Table 4 indicates the applicability of the VI to other mines. Along with the 14 mines listed in **Table 3** are three further categories:

- **Same structure:** This means that the materials, construction and characteristics would be close enough to yield an identical VI. Direct copies, licensed versions or

close variants fall into this category. Twenty mines are listed, of which five are believed to have been used in significant numbers.

- **Similar structure:** mines that share most of the characteristics of the mines examined in the study. These mines incorporate technical variations that would not significantly alter their aging characteristics. The VI for these mines could be expected to be within two points of the original. Twelve mines are listed, all of which are believed to have been used in significant numbers.
- **Some similarity:** These are mines with significantly different designs, yet share enough characteristics for the VI to have some validity. It is likely that the VI for these mines would be within four points of the original (though some may be closer, or even the same). Forty-seven mines are listed, of which 35 are believed to have been used in significant numbers.

6.2.1.5. Modifiers

The Vulnerability Index represents a significant but rough first step at quantifying the measurement of vulnerability to degrade and change over time for both a complete mine and its major components. However, further field analysis, testing and collection of data to support this model is required in order to develop a refined tool that can be used with confidence.

One challenge is understanding the impact of microenvironmental differences for same mine types on mines in varying locations. A first attempt to answer this question, undertaken by the JMU Department of Geology and Environmental Science, was hampered by uncontrollable factors related to landmines recovered from the field—namely, the lack of same mine types in our two locations. Even so, broad observations pointed to significant differences in degradation based on environment; this observation is supported by anecdotal field expertise and supplemental mine analysis conducted in the Falklands and other countries during the course of this research.

As indicated by the ‘Modifiers’ listed in **Table 3**, the team has identified the importance of external variables in the consideration of Vulnerability Index. As is discussed later in Section 5.4, future research should further explore the potential equation developed in the current Aging Study research effort:

$$\text{LMR} = \text{VI} * \text{E} / \text{T} \text{ (Live Mine Risk} = [\text{Vulnerability Index} * \text{Environment}] / \text{Time})$$

Due to current research phase limitations and the need for matched landmine/soil pairing across different locations, this concept remains to be further explored and tested in future phases of research on landmine aging. Even the concept of ‘environment’ as such required nuanced approaches to understanding and measuring a mine’s VI within a certain context (e.g., water, UV, soil).

VI is currently a low-resolution model which provides a means to understand the relative vulnerability to degradation of different mines. The model can be refined by further work on the ranking of materials (types and thicknesses) and examination of weighting factors.

Table 1. Materials and resilience to degradation

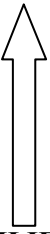
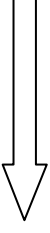
	Materials list	Abbreviation	Notes
<p>Higher</p>  <p>RESILIENCE</p>  <p>Lower</p>	Epoxy composite	EC	<ol style="list-style-type: none"> 1. 'Resilience' ranking is based on field observation of deterioration through aging. 2. <i>N/A</i> (not applicable) used where component is absent 3. Boosters are not considered because they will be the same as, or higher quality than, main charge rating 1 4. Initiators may be percussion or stab-sensitive, in AL or CU capsules or tubes, but all are vulnerable through their thin seals (generally foil, gauze or lacquer). VI, therefore, is mainly determined by their position rather than their construction. 5. Where striker is absent, use same VI as Firing pin
	FiberGlass	FG	
	Bakelite (or thermosetting plastic)	B	
	Stainless steel – thick (> 1 mm)	SS+	
	Stainless steel – thin (<1 mm)	SS	
	Copper	CU	
	Polycarbonate and Acetates	PC	
	Thermoplastic - thick (>1 mm)	TP+	
	Thermoplastic - thin (<1 mm)	TP	
	Mild steel – plated or thick	MSP	
	Aluminum – thick (> 1 mm)	AL +	
	Aluminum – thin (<1 mm)	AL	
	Mild steel – unplated or thin	MSU	
	Rubber – thick (> 1 mm)	R+	
	Rubber – thin (<1 mm)	R	
	Wood	W	
	Cardboard	C	

Table 2. Component Vulnerability Index

Rating	Cover/top	Casing	Striker	Firing pin	Spring	Initiator	Main charge
1	B,FG	FG,B	SS+,PC	SS+,PC	EC,FG	Double encased capsule	Comp B, Tetryl, Pressed TNT
2	MSP, TP+	PC	SS,TP	SS,TP	SS/+	Well protected	Cast TNT – high grade
3	MSU	MSP,T P+	AL+	AL+	MSP	In internal void	Cast TNT – low grade
4	R+	MSU,T P	MSP	MSP	MSU	Vulnerable position	Soluble mixtures, LE
5	R, W	W	MSU	MSU	R/+	Little or no protection	HME

Table 3. Vulnerability of mines by type

COMPONENTS	MINE TYPES													
	PMN	PMN-2	PMD-6	M35	M14	M6	M15	M16	M19	MD-82B	P4 B	SB-33	SB-81	Type 72
Cover	4	4	5	2	2	2	2	4	1	2	3	4	2	5
Casing	1	3	5	3	3	3	3	4	1	3	3	2	2	3
Striker	4	3	4	2	4	4	4	4	1	5	2	1	1	4
Firing pin	4	4	4	2	4	4	4	4	1	5	1	1	1	4
Striker spring	3	3	3	2	1	3	3	3	1	4	3	3	3	1
Cap	2	3	5	2	2	2	2	4	2	4	1	2	2	3
Main charge	1	1	1	3	1	1	1	2	1	1	1	1	1	1
Vulnerability Index (VI)*	19	21	27	16	17	19	19	25	8	24	14	14	14	18

*Possible modifiers include environment, soil type and degree of exposure.

Table 4. Mine comparisons

MINE TYPES	VI	SAME STRUCTURE (Same VI)	SIMILAR STRUCTURE (VI +/- 2)	SOME SIMILARITY (VI +/- 4)
PMN	19	MS-3, Type 58, Iraqi PMN COPY	GYATA-64, PM-79	FMK-1
PMN-2	21			
PMD-6	27	PP Mi-D, TYPE 59, PMD-1		APP M57, PT Mi-D, TMD-44, TMD-B, ATM-44, TMD-1
M35	16		M409, MAPs, M411, M/969	PRB-M3
M14	17	Indian version (AP NM M14), M/56	MN-79	PP Mi-NA 1
M6/M15	19			M/71, Mk 7, No 6, Tellermine 35/42/43, TM-46/57/62M, TMM-1, Type 72 (Metallic), UKA-63
M16	25	Indian and South Korean versions	OZM-3, Type 69	DM-31, M2, M/966, No. 12, NR-442, OZM-72, PP Mi-Sr, P-S-1, PSM-1, S-mine
M19	8	Chilean, Iranian, South Korean and Turkish versions		
MD-82B	24			P2 Mk2, P4 Mk1
P4B	14	P4A	C3B	No. 10
SB-33	14	EM-20, M/412, P-5	MAUS, VS-MK2	TS-50, VAR/40, VS-50, YM-1, YM-1b
SB-81	12	M/453, YM-II		SH-55, TC/2.4, TC/3.6, TC/6, VS-1.6, VS-2.2, YM-III
Type 72	21			DM-11

6.2.2. Mine lifespan charts

The lifespan charts consider three key periods in the life of a mine contamination problem:

- Laying period—the time from when the first mine of the type is laid in a country or region, until the last mine of that type is laid;
- The lifespan of components that neutralize on failure;
- The lifespan of components that disarm on failure.

The first mines laid are expected to fail over time along a normal probability distribution. The last mines laid are expected to fail following the same failure probability curve.²² In each case different components will fail along their own probability curves, some resulting in neutralization, some in disarmament.

In **Figure 1**, the neutralization element of the bar covers the period until all components which neutralize on failure can be expected to have failed. The disarmament element correspondingly reflects the duration until all components which disarm on failure can be expected to have failed. For convenience the different elements of the bar can be overlaid, as shown in *Error! Reference source not found.2*. In general it is expected that neutralizing components (springs, pins, etc.) will tend to fail before disarming (explosive) components. It is possible that in some mine types explosive elements will deteriorate and fail before neutralizing items.²³

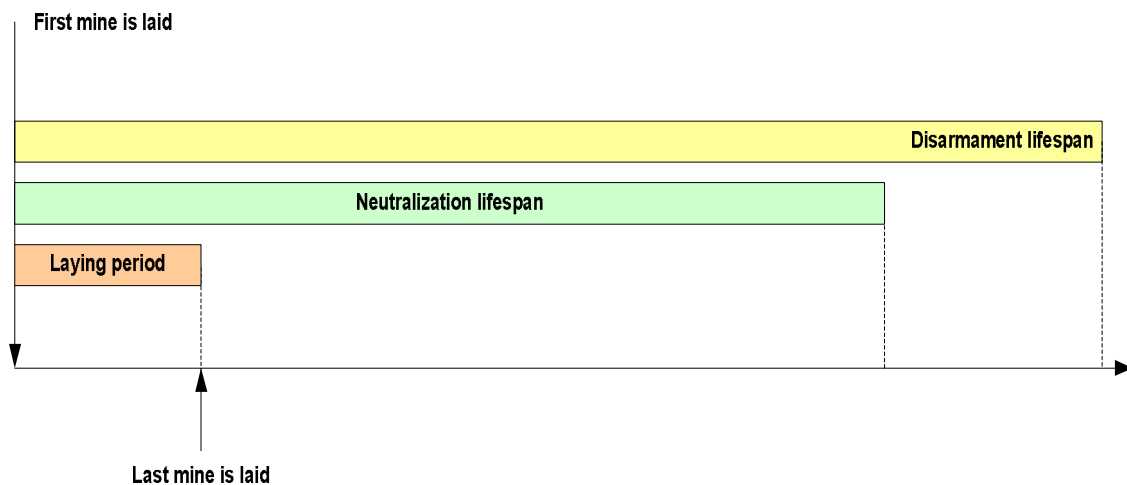


Figure 1. Sample Mine Lifespan chart

Within an affected country it is likely that there will be several types of mine present. The overall chart for such a country would look as in **Figure 2**. For each type of mine (in this

²² This means that the model does not take into account any degradation which might occur during the period between manufacture and placement into the ground. In some instances, poor storage conditions may be a significant factor in aging processes.

²³ A possible example of this situation could be found with PFM-1 mines where a casing breach would result in run-off or evaporation of the liquid explosive, while the metallic components of the firing train might remain in good condition.

case three types; A, B and C) a lifespan bar indicates the history of the type from the period during which laying took place through to the projected end dates for both neutralization and disarmament.

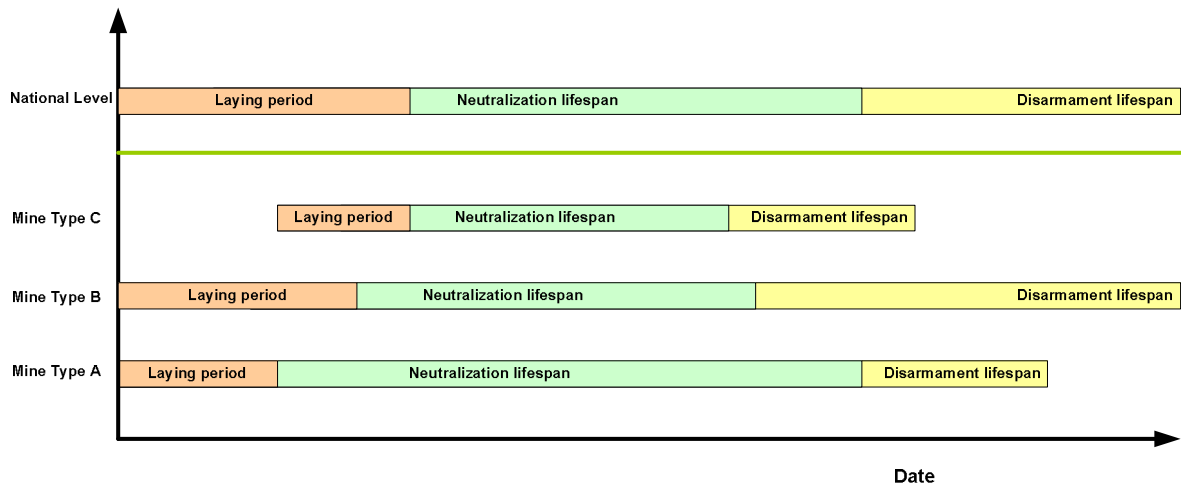


Figure 2. Illustrative country overview

At the national level the various subsidiary bars can be further aggregated to describe the overall national landmine contamination lifespan, through to the point at which it is unlikely that any landmines remain in an actual- or potential-functioning condition within the country.

The length of each bar is related to the vulnerability of the mine type under the environmental conditions found in the region where they are laid. At this stage there is no reliable mathematical relationship between the VI of a mine and the length of its lifespan, but it can be said with some confidence that mines with higher VIs will have shorter lifespans. Thus, in the illustration in **Figure 2** mine type C is likely to have a higher VI than mine type B.

It is also possible to extrapolate between types and regions to say that similar mine types, with similar VIs, are likely to respond to similar environmental conditions in similar ways; the lifespan bar of a wooden box mine in one hot wet environment is likely to be similar to that of another wooden-cased mine in another hot, wet area. Mines that contain similar components (such as strikers and pins) manufactured from similar material can be expected to exhibit similar degradation and failure patterns.

6.3. Using the tools

Both tools have potential value for planners and policy makers. Anecdotal evidence from field programs suggests that landmine aging issues are already becoming increasingly important within clearance operations.

It is too early to be able to provide site-specific guidance to operators about the likely condition of the mines they encounter, but it is already reasonable to provide general input to planning processes about the possible condition of mines. In particular

information from aging studies may be able to assist field operators in carrying out valid risk assessments, so allowing them to apply the most efficient search and clearance techniques.

For operational planners the tools already provide some useful input into prioritization questions; it is clear that some mines are likely to remain hazardous for much longer than others. It is reasonable to take such information into account when assessing the likely level of risk posed to populations in mine-affected areas.

For policy makers the lifespan charts are likely to become of considerable importance (accepting that a good deal more data will be required before reliable projections can be made for most mine types in most countries). Some mines are likely to remain active for extended periods while others will become inoperable relatively quickly; indeed some populations of some types are already essentially 'dead'. For long-term planning purposes, it is sensible to assume that even the most intensive and long-lasting programs will miss some mines. Where particularly durable mines (those with a low VI) are present, policy makers will need to take account of such information when considering the scale and duration of residual capacities in affected countries.

6.4. The need for more data

It is important to make clear that, while both tools have a strong internal logic, both of them will benefit from access to much more data about the condition of landmines and their critical components. The data available within this study is limited. The tools will yield their full benefit only when they are primed with as much data as possible to allow application of recognized statistical techniques. Even so simple a datum as a geo-referenced photograph of the landmine in situ would be a valuable contribution to a broader Aging Landmines Data Repository, provided adequate metadata were captured at the same time.

That data is not generally available, to a great extent because field programs have not been in the habit of recording information about the condition of mines. One of the key recommendations of this report is that field operators should be strongly encouraged to start gathering, and reporting, basic data about the condition of mines. The study team do not want field operators to try dismantling mines, but information about the external condition of mines when they are found, gathered on the basis of a brief non-contact visual inspection, would be of the greatest value in improving the reliability and utility of the tools described here.

6.5. Policy and compliance implications

Development of the tools raises some difficult, but important issues, which policy makers may wish to consider. The affects of aging on a mine may result in temporary or permanent neutralization of the device (that is when some obstruction prevents the mechanism of the mine from functioning) and/or its disarmament (that is when part of the explosive chain is no longer present), probably permanently, but possibly temporarily.

A neutralized mine retains all its component parts, but is unable to function. A disarmed mine may no longer contain all its components. Some explosive material may have been washed away or it may be that some originally explosive material has undergone a chemical change which means that it is no longer an explosive; there is simply some inert substance in its place.

The ways in which aging effects prevent a mine from functioning have clear implications for the safety of operational deminers, but there may also come a point, after permanent disarmament through degradation of explosives has occurred, when the device is no longer capable of acting as a landmine. While the study team would not suggest that leaving mines to rot would generally be an acceptable tactic in mine-affected areas, drawing on aging information when taking decisions about residual capacities, following the end of major clearance operations in a country, may well be justified.

Questions about when a mine stops being a mine are contentious ones, but it would be remiss of this study to ignore aspects of landmine aging which may have practical implications in the real world.

7. Conclusion and Recommendations

7.1. Conclusions

In more general terms, at the beginning of this project little was understood about landmine aging. As a result of the work done to date the situation has become a good deal clearer. While it is clear that more work needs to be done it is already apparent that landmine aging is of importance now, to field operators and to policymakers and planners.

Specifically, development of user tools has highlighted the following conclusions:

- Landmine aging is an issue now; it will become more and more important as time passes.
- The vulnerability of different mine types to degradation over time can be assessed and indexed.
- Further statistical analysis should help predict the likely lifespan of different mine types under various conditions;
- Policy makers should consider the implications of landmine aging for residual capacity and public health questions.
- Policy makers may wish to consider the implications of landmine aging for ‘end state’ questions about landmine contamination situations;
- User tools can be improved and expanded to more mine types through the (safe) collection of as much field data as possible.
- Further review of existing literary sources is likely to yield useful input to help refine aging models.
- Further laboratory investigation of the most vulnerable components of mines will help refine aging models.

7.2. Conclusions from field evaluation

- The comparison of various mine types of similar age²⁴ within differing climates gave the study team an insight into the various causes of degradation. Although there are many factors that may contribute to the speed and nature of the aging process, the majority are of little significance. Basic environmental elements, such as temperature, rainfall, exposure to sunlight and fire, account for the vast majority of the effects.
- Analysis of recovered mines revealed a number of failure mechanisms. Many, such as the rusting of springs or seizure of moving components, are applicable to a range of mine types.

²⁴ Most date from the 60's and 70s, and have been laid for around 30 years.

- The major complication for this study was that, with the exception of the Russian PMN, different types of mine were found in the regions visited. This severely limited the opportunity for direct comparison; however, many of the mines examined did use similar materials and incorporated comparable mechanisms.
- Overall, the mines in Cambodia were in worse condition than those seen in Jordan, Afghanistan or the Falkland Islands. This appears to be due primarily to the action of water on vulnerable materials, such as wood, rubber and mild steel.
- The Russian PMN offers the greatest insight into the factors governing deterioration since it is present in both Afghanistan and Cambodia. The PMNs in Afghanistan are mostly in better condition than those of similar age in Cambodia; this suggests that the wet climate of Cambodia accelerates degradation and contributes significantly to the failure of these mines.
- Mines in the extremely harsh, wet climate of the Falklands were in surprisingly good condition. This is evidence that climate alone does not dictate the rate of degradation. The mines in the Falklands have robust outer casings and have, mostly, remained watertight.
- The study offers compelling evidence that the presence of water within the casing substantially accelerates the deterioration process. There are, therefore, two distinct stages in the degradation process:
 - Effects leading to the breach of the outer casing
 - The accelerated degradation of internal components once water enters the mine.
- The consistency of degradation within vulnerable materials²⁵ allows extrapolation to similar materials and components in other mines. Where degradation contributes to a failure mechanism, this too can be expected in mines with similar structures and fusing systems.
- The study indicates that all mines will eventually become incapable of functioning as designed due to the effects of aging. The rate at which this occurs is largely dependent on the local environment and the materials used for vital components.
- Degradation effects such as the rotting of wood, perishing of rubber and rusting of mild steel are so well known and well documented that their existence and primary consequences need little justification.
- All of the mines examined were becoming less likely to function (and therefore safer) as they aged; however, there are a few mines²⁶ which might become more sensitive before they eventually become safer. It is also possible that some mines containing pyrotechnic compositions²⁷ might become non-functional when damp, but then become viable again if they dry out.

²⁵ Degradation effects such as the rotting of wood, perishing of rubber and rusting of mild steel are so well known and well documented that their existence and primary consequences need little justification.

²⁶ In most instances, failure of the mine was due to degradation of mechanical fuse components.

The explosive train tended to remain intact for longer than the fusing mechanisms.

²⁷ Pyrotechnic compositions often feature at the beginning of the explosive train, in order to translate a mechanical action into ignition, similar to striking a match.

7.3. Recommendations

It is recommended that:

- Field data is collected systematically. Understanding landmine aging at the country level requires extensive statistical analysis. That analysis can only yield reliable results when there is a substantial body of data to work from. It has not been normal practice for clearance operators to collect and report information about the condition of landmines discovered in the field. It is of the utmost importance that such data be collected on a routine basis from now on. An
- example template for capturing the required data is at *Annex K*.
- The initial aging models developed within this project should be refined, enhanced and extended to incorporate improved statistical techniques and to encompass other common types of mines.
- National authorities, Mine Action Centers and field operators should be strongly encouraged to start collecting and reporting information relating to the condition of landmines as and when they are discovered. Understanding landmine aging at the country level requires extensive statistical analysis; that analysis can only yield reliable results when there is a substantial body of data to work from. It has not been normal practice for clearance operators to collect and report information about the condition of landmines discovered in the field. It is of the utmost importance that such data be collected on a routine basis from now on.
- Statisticians become involved in the study. As field data become available thorough analysis by statistical specialists should be carried out to identify failure patterns and to make projections about the likely lifespan of different mine types in different areas. The reliability of such projections is likely to increase as more data become available and over time.
- The study is continued.

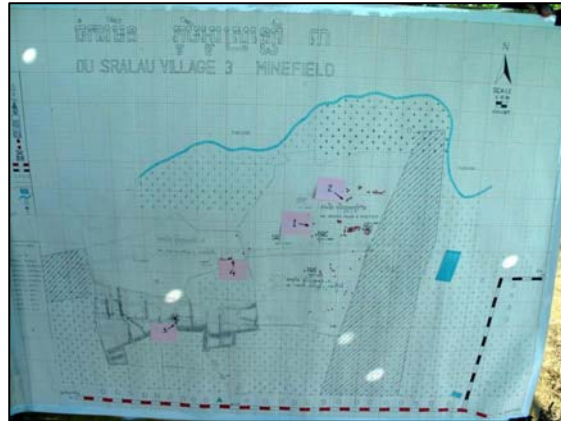
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A: Sequence of Events, Field Recovery of Mines



Arrival on site, followed by orientation and safety briefing



Review of objectives and formulation of mine recovery plan



The team moves into the field, complete with PPE and medic



A deminer confirms location of each mine and begins excavation



The deminer ceases excavation as soon as the mine is visible



The recovery team continues to uncover the mine with minimal disturbance



A complete photographic record is made
As the mine is uncovered



The temperature of the ground near the
mine is measured



Soil from the ground in contact with the
mine casing is recovered and labeled



The mine is removed from the ground, disarmed
and examined



Every step of the process is recorded, along with the
coordinates of the mine



Recovered mines, complete with detonators, are
packaged for transportation

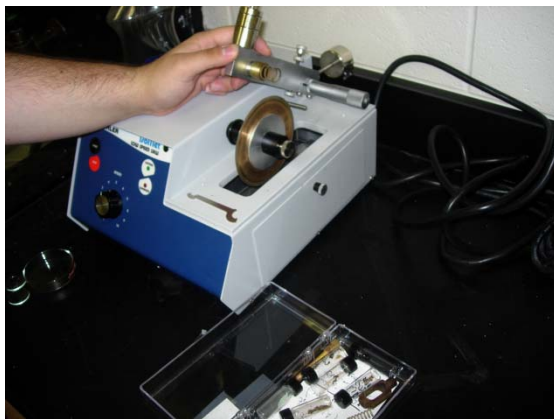
B: Sequence of Events, Analysis of Metal Corrosion²⁸



Parts from each mine are photographed



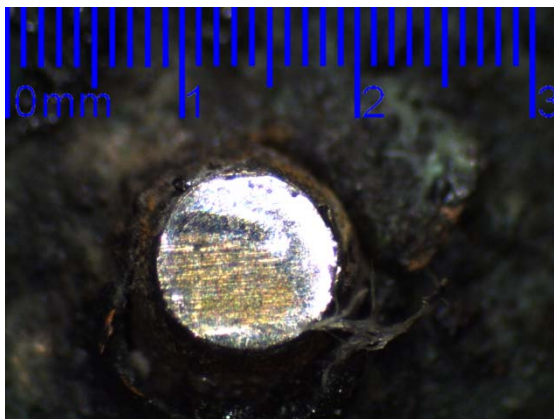
Surface corrosion of metal parts is documented using binocular microscope



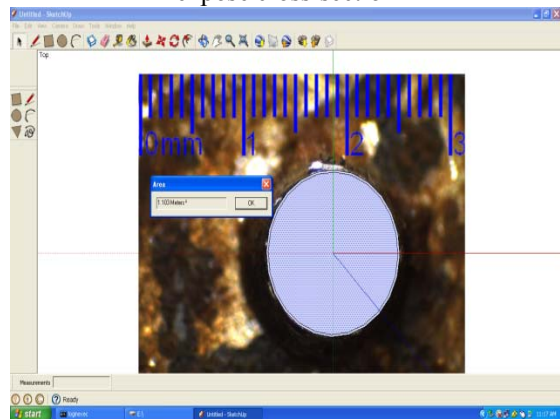
Parts are sectioned using a slow-speed diamond saw



Cut surface is polished with diamond paper to expose cross-section



Cross-section is photographed



Cross-sectional area lost to corrosion (for pins) is quantified using Google Sketchup

²⁸ All photos by EJ Estes and Dr. Liz Johnson, except for the image of the SEM, which was taken by Dr. Lance Kearns.



Samples are mounted on carbon-coated Scanning Electron Microscopy mounts



Textures and qualitative compositions of metal parts and materials produced by corrosion are analyzed using the Scanning Electron Microscope at JMU



Samples are archived in labeled boxes

C: Landmine Materials²⁹ and Environmental Soils³⁰ Literature Review

This general literature review examines empirical data related to common materials associated with landmines within the context of degradation and other effects of potential environmental characteristics and processes. The first section examines the chemical and physical processes that apply to materials making up the outer casing of the landmine. The second section reviews the internal workings of the landmine and how internal and external processes affect key materials. Both of these focus on how landmine materials are potentially altered by its environment. The third section examines materials in the context of environmental and soils analysis and modeling.

The overall concept of this investigation is that an outer layer of the landmine must be breached in some manner for the decomposition of the critical components. These critical components include things like springs, firing pins and explosive components. This review tries highlights how these components can be degraded by the environment. Although this may not be all-inclusive it should give an overview of the major processes that cause the eventual failure of the landmine. Some other concepts that need more information are: a way to do a time-resolved analysis of aging galvanic cells, and older data on metal degradation which has been in this review unattainable. The data is most likely out there but due to the age of the data wished to be reviewed in this paper, is most likely not digitized.

1. Materials: the landmine's outer defense

Most landmines have an outer shell, usually plastic or metal³¹; this outer body is the first barrier that these mines count on to stay functional. If the outer case of the mine is never breached and remains airtight then most landmines can remain functional almost indefinitely. However, this is often not the case; most landmines' outer casings are vulnerable to outside influences that will cause outer casing components to break down. This section discusses what some of these various processes could be and how they relate to the over all functionality of the landmine.

1.1. Fire damage

Fire can have multiple effects on a landmine. Some effects can potentially cause the increase in the decay of the mines; others effects may extend the life of the mine. In order to help understand effects of fire, it is necessary to determine the depth that heat can travel in various soils. Bradstock (2005), Busse (1940) and Beadle et al. (1995) provide

²⁹ By Everett J. Estes III, James Madison University

³⁰ By Dr. Tony Hartshorn and Jeremiah Vallotton, James Madison University

³¹ Some mines have wood or other casings, but the focus of this literature review is primarily on plastic and metal materials.

various data showing the depth and intensity of heat penetration of fires in various soil conditions. 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.

The first factor is a simple concept: the more water that is in the soil at the start of the fire the lower the maximum temperature will be. This can be modeled using the following equation (Busse et al., 2005).

$$\ln(T) = 4.689 - (0.196 * \text{soil depth}) - (1.06 * \text{soil moisture}) + (0.00038 * \text{heat load})$$

This equation has an approximate r^2 of .77, which may not be suitable for high accuracy modeling; however, for the purpose of the research it is more than acceptable. This equation is said to be usable for all soil types (Busse et al., 2005); however, this seems potentially suspect. Still, this equation is certainly more than adequate as a starting point for any modeling that might be done in the future. **Figure 1** shows results of the research by Busse et al. (2005).

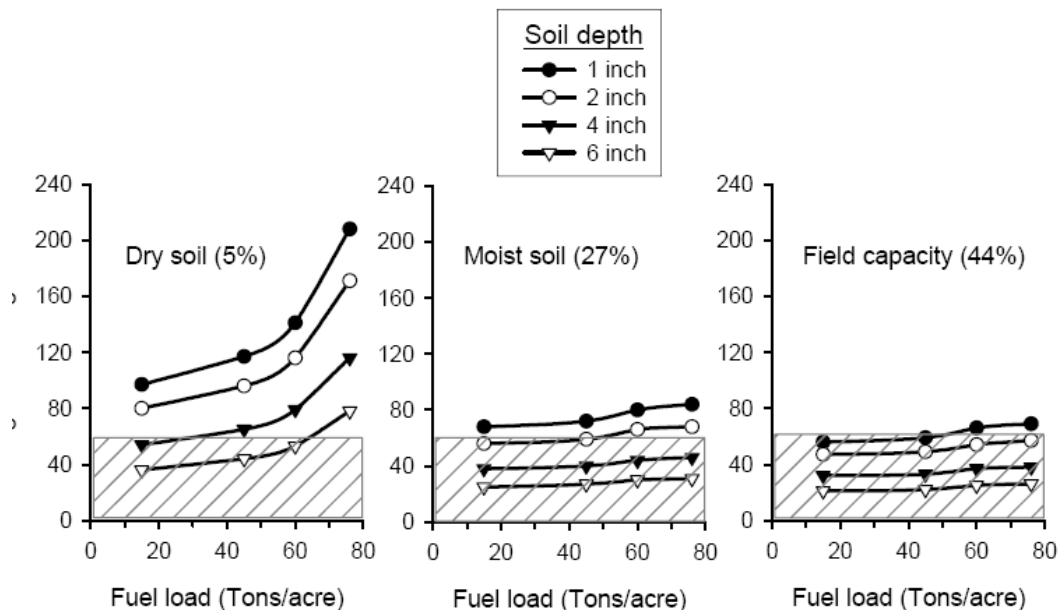


Figure 1. Predicted maximum soil temperatures during burning of masticated fuels as a function of soil moisture, soil depth, and fuel load. The gray-shaded area in each graph represents sub-lethal temperatures for roots. Volumetric soil moisture content is shown in parentheses in the graph titles. Field capacity is equivalent to the maximum available water content found within 24 hours of a saturating rainfall (Busse et al., 2005).

The second parameter, time of the fire over an area, is addressed by Beadle (1940). Although Beadle does not include any equations as to how to predict the temperature increase as a function of time, the data does show that there is an obvious increase in how long the fire is in an area to how temperature in the soil increases (**Table 2**). This work is complimented by research by Bradstock and Auld (1992, 1995), and in conjunction with Beadle's work, the approximation can be made that most typical and flash fires will have difficulty getting soil temperature higher than 150°C past 3 inches (7.6 cm). In the 1-2 inch (2.5-5.1 cm) range the temperatures can get as high as the 200°C.

Literature findings of this nature relate to landmines based on the simple understanding that plastics and metals have physical and chemical changes during times of increased temperatures. Whether one is talking about plastics or metals, several things may be understood. First, there will be a temperature gradient where the upper portion of the mine will be at a higher temperature than the bottom. For metals this may stabilize quickly due to the thermal properties of the material, so that the mine will equilibrate to be the same temperature much faster than plastic or a material with a lower thermal conductivity. An additional assumption, also based on the same principal, is that the interior of the landmine will be cooler than the outer portion. Due to the thermal properties of metals it is likely that in the same temperature conditions, the interior of a metal landmine will be at a higher temperature than that of a plastic one.

The differences between these metal and plastic materials when exposed to heat are almost self-evident. Metals will have little to no physical deformation. However, if a plastic reaches its glass transition temperature, which is different for all plastics (see **Appendix I**), the plastic will soften and start to disfigure. If the temperature reaches the plastic's melting point and the plastic is a thermoset, it will burn and break down. If the polymer is a thermoplastic, it will disfigure more rapidly. If the temperature is high enough both polymer types will be burned, causing them to become more rigid and potentially crumbly.

It is also important to note that some rubbers may undergo a primitive form of vulcanization where the polymer will become more durable. This is done by the scorching or hardening of the outer layer of polymer. This causes the outer surface to become more resilient to physical and chemical degradation. Metals, on the other hand, will most likely not reach a temperature that will cause them to soften and will most likely only have superficial damage from the heat.

1.2. Weathering of plastics

The weathering of plastic materials predominates the outside of the landmine. This is primarily due to the constant contact with the environment. This would include the

abrasive force of soil and other earthen particulates, exposure to light if unearthed, contact with water and its solutes as well as human contact such as farming equipment, wastewater, industrial and other pollutants. This section addresses the weathering on the landmines through the means of artificial weathering.

The data from Boubakri et al. (2010) and Zhao et al. (2010) were obtained by using mainly ultraviolet (UV) light to weather the materials plus other above-ground weathering agents. Though above-ground analysis is not ideal for extrapolation to landmines, it appears to be the predominately accepted method that is currently being used. It would be more applicable if it was designed to show weathering using underground agents.

Boubakri et al. (2010) and Zhao et al. (2010) use similar techniques to study the weathering effects on rubbers. In this case, although they are studying different types of rubbers, these processes are applicable to most polymers. Their findings indicate that UV degradation of polymers will increase the cross-linking between polymers, which will, in turn, increase the polymers' overall tensile strength while decreasing their ability to stretch. What this means is that if something made with polymers requires a certain amount of flexibility to operate, then this process will start to impede that flexibility and potentially, overall functionality.

For hard plastics, however, this cross-linking effect is mostly unobservable except for a potential color change. This color change can be used to measure the amount of additional cross-linking by using the yellow index which is discussed in Zhao et al. (2010) , which was calculated using the Flory-Rehner equation.

$$v = -\frac{1}{V} \left[\frac{\ln(1 - VR) + VR + \mu VR^2}{VR^{1/3} - \frac{VR}{2}} \right]$$

Here, v is the crosslink density (mol cm^{-3}); VR is the volume fraction of polymer rubber after immersion in organic solvent; V is the molecular volume of organic solvent ($\text{cm}^3 \text{mol}^{-1}$); and l is the interaction parameter between the rubber and organic solvent. The rubber is found to begin to fracture and become dull. Other mechanical properties seem to weaken but then increase; for example, the elastic modulus, stress and strain test (Boubakri et al., 2010). This seems to suggest that as the polymer creates cross-links it starts to weaken because it is losing other bonds that are stronger than the cross-links. However, as more cross-links are formed the polymer gains strength. It is worth noting that as the polymer becomes more rigid it becomes easier to break, even though the overall tensile strength is stronger.

2. Materials: The landmines' inner workings

This section of the review focuses on the internal mechanisms of failure for the landmine. This includes the creation of galvanic cells, degradation of the explosive component, corrosion of the metals not related to the galvanic cell, and some aspects of the modeling of the processes of the flow of explosive residue from the mine. These processes lead to the actual failure of the landmine to function as intended, as opposed to the breaking down of the outer casing.

2.1. Galvanic cells

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. However, due to the complexity and concentration dependence of these they will only be mentioned. The reason behind this is that a galvanic cell potential is determined based on the different salts, metals and their concentration. Because these will always be in flux it is not truly possible to determine the cells' potential, which is the measure of how reactive they are. Being that the cell is dependent on concentration, its potential can change even what will be oxidized and reduced. This means that trying to predict the cell potential is most likely futile. However, it is known that the cell is there and taking place. Doing a specific study of this effect maybe useful in the future.

2.2. Explosive degradation

Taylor et al. (2009) gives data on how explosive particles dissolve in an outdoor environment. This is not the best match for the data in terms of this review; however, this data does give an estimation on how long it takes to dissolve a certain mass of explosive in a completely free environment. For the purpose of understanding how this relates to landmines, this gives a maximum possible loss of explosive that should be taken into account when trying to model the behavior of landmines in the environment (see **Figure 2** and **Table 1**). Several observations should be taken into account when trying to use this data as a starting model; the first being that this data is heavily reliant on surface area. This should be accounted for by linearly coupling the increase in loss with the increase in surface area. Furthermore, this was done with free-flowing water, not stagnant, which is what would be most likely found in the landmine.

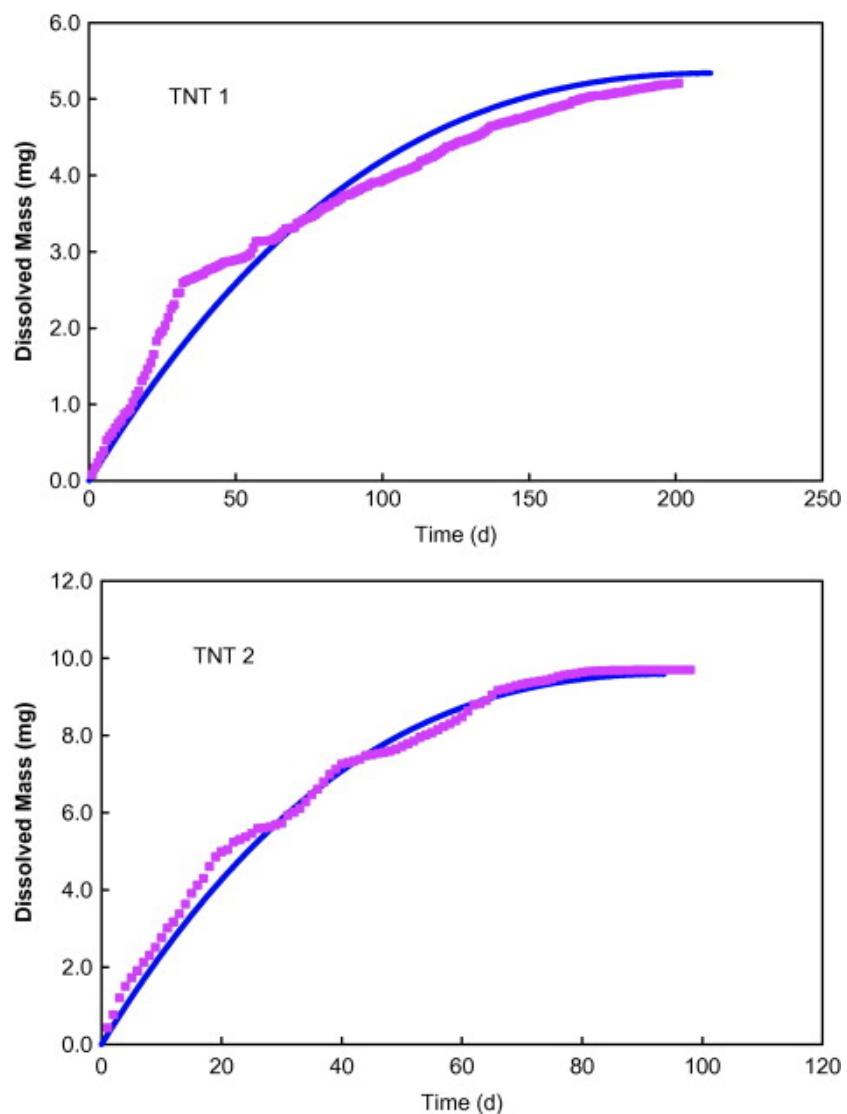


Figure 2. Dissolved-mass versus time for the TNT test particles (symbols are measured values, smooth curves are modeled values) (Taylor et al., 2009).

Table 1. Dissolution test parameters and the recovered mass for HE particles (Taylor et al., 2009).

Particle	Drip Rate (mL h ⁻¹)	Initial Mass (mg)	Dissolved-Mass (mg)	Time (days)	% Mass Recovered
TNT 1	0.5	5.34	5.33	201	99.9
TNT 2	1.0	9.59	9.70	98	101
Tritonal 1	0.5	1.89	1.28	72	67.8 [±]

Particle	Drip Rate (mL h ⁻¹)	Initial Mass (mg)	Dissolved-Mass (mg)	Time (days)	% Mass Recovered
Tritonal 2	1.0	6.40	5.02	73	78.5 [‡]
Comp B 1	0.5	2.31	2.23	200	96.5
Comp B 2	1.0	9.09	9.03	141	99.4
Octol 1	0.5	6.53	2.15	101	33.9 [‡]
Octol 2	1.0	17.33	9.92	140	57.2 [‡]

[‡] All the TNT mass

Agitation of the explosive-water interface speeds up dissolution in most cases. From Lynch et al. (2002) there is data pertaining to the effect of rotating, heating, surface area and vibration on the dissolution of explosives. The effect of rotation caused an increase in dissolution of all compounds, which is what would be expected. The increase in heat also increased the ability of the chemicals to be dissolved. The surface area had the same increase as the rest with the exception of RDX, which was stable regardless of the surface area. The vibrational affect was similar to that of the rotation in that all the compound had an increase in solubility. Lynch et al.(2001) also does a comparison of different pH levels and found that at low acidities there was not a distinguishable change in the dissolution rates. This might alter at more basic pH but this would be outside the realm of environmental conditions and is outside the scope of this investigation.

Irrazábal et al. (2009) provide an explanation of the transport of solvated explosive from a landmine into the soil. It states that the concentration of the solute can be determined by equation below

$$\begin{aligned}
 -\frac{\partial C}{\partial t} = & -\nabla \cdot (C_v K_v \nabla P_v) - \nabla \cdot (C_l K_l \nabla P_l) - \nabla \cdot (D_c \nabla C_l) \\
 & + r + \frac{\partial}{\partial z} g(C_v D_v \rho_v + C_l D_l \rho_l) + \rho_r \frac{\partial C_R}{\partial t}
 \end{aligned}$$

Here, C is the solute concentration; indices v and l represent the amount of the vapor and liquid phases; K is the permeability; P the pressure; CR represents the adsorption of species in the porous media; p the density; D represents diffusivity in both phases according to the index; z the axis of the system parallel to gravity; r represents the chemical or biochemical reaction term; pr the density of the adsorbed phase; and g is the acceleration of gravity.

This equation can be used to help model flow of explosive from the mine. This may also help give the project different avenues for future research. It also provides data on soil parameters that will help when trying to model this in different soil conditions as seen in **Table 2**. In addition, Morley et al. (2006) and van Genuchten et al. (1980) provide base equations that will be useful in creating the models from the ground up. Alzate et al. (2006) has special IR data on TNT that may also be used as a reference for future research (see **Appendix 2**).

Table 2. Chemical and soil properties (Irrazábal et al., 2009).

Definition	Parameter	2,4,6-TNT	2,4-DNT
Liquid-gas partition coefficient (Henry constant)	K_H (25 °C)	8.2E-7	1.0E-5
Soil-liquid partition coefficient	K_d	5.7	2.9
Soil-gas partition coefficient (K_{sc})	A_0	15.3	13.1
	α	51.2	43.5
Liquid diffusion	D_l (cm ² d ⁻¹)	0.580	0.632
Gas diffusion	D_g (cm ² d ⁻¹)	5530	5790
Molecular weight	MW	227.13	182.14
<i>Soil properties</i>			
Permeability	K' (m ²)	8.4E-12	
Porosity	ε	0.43	
Fully-saturated conditions	S_s	0.999	
Liquid residual saturation	S_{lr}	0.1046	
Matching saturation	S_l	0.1105	
Air entry pressure parameter	$1/\alpha_{wg}$ (Pa)	676	
van-Genuchten fitting parameter	n	2.68	
van-Genuchten fitting parameter	$m = 1/n$	0.373	
Bulk soil density 1.5 g cm ⁻³	ρ_b (g cm ⁻³)	1.5	

2.3. Corrosion of metals

Metal corrosion can be characterized as the interaction of elemental metal plus water going to metal hydroxide and aqueous hydronium ion. This is the basic reaction of any metal corrosion. When the metal cools, areas of chemical instability will accrue. This then creates a site for accelerated decomposition in the metal. Ryan et al. (2002) describes how the change in the composition affects the corrosion process of stainless steel. However, this covers only stainless steel and is analyzing modern techniques for creating the stainless steel. Assuming that the metal specimens that are being examined are made with inferior techniques and metals, it can be assumed that this process will be accelerated. This, in combination with the galvanic cells, will cause the majority of the degradation of the metal. Also, decomposition of metals is not the only degrading process—plating/deposition was observed in Phase 1's seized-up PMN strikers.

3. Environmental and soil effects on landmine degradation

This section reviews literature linking research of materials, landmine degradation and environmental indicators or factors (soil, climate, etc.) that may allow predictive changes in landmine functionality.

3.1. Literature related specifically to landmines and degradation

Literature related to the Aging Study's core research questions are limited. Much of the literature related to landmine research and development within the context of environment focuses on different ways we can detect landmines and UXO for removal with geophysical technologies (e.g., Billings and Bearing, 2010; Prouty, 2010; Phelan and Webb, 2003) or how environmental conditions affect the efficiency of detection procedures (e.g., Kuznyetsov, 2008; Preetz et al, 2007).

However, there are a few pertinent publications. Colin King writes about both the rusting of tripwires on certain mines in wet climates as well as general principles of landmine degradation (King, 2007; King, 2010). Stevens (2009) focuses on the use of surveys to determine mine risks, as well as general things that cause landmine degradation.

van der Merwe (2002) and others (e.g., Gebrehiwot and Hamdi, 2009) simply argue that it is necessary to find alternative ways to figure out the functionality of mines besides clearance, as clearing every mine is too expensive. They do not, however, address actual measurements of functionality.

Jebens (2010) talks about the degradation/loss of functionality of landmines set near beaches in Denmark. This paper is probably the most useful, as it contains multiple sets of data and graphs relating to mine degradation and potential causes of it. For example **Table 3** identifies environmental data and potential functionality of samples in Skallingen, with red indicating mines likely to function as intended and yellow indicating mines unlikely or unable to function. In this study, the author notes that most fuzes are observed to have a plug between the hammer and percussion cap, except for a number in the dunes; and that the majority of percussion caps were not found to work regardless of the environment but a number could work inside a protective dune environment. It was also noted that if the fuze, percussion cap and detonator are functional, the stock mine and wooden case are likely to work. In general, the Teller mine was still found to be functional.

Table 3. The functionality of fuses, detonators, percussion caps and mines found in different coastal environments on Skallingen (Jebens 2010).

	A	B	C	D
1	Sub Area	Sample	Elevation	pH
2	Marsh	1	1-1, 5m	7.1
3	Marsh	2	1-1, 5m	8
4	Marsh	3	1-1, 5m	6.7
5	Marsh	4	1-1, 5m	8
6	Marsh	5	1-1, 5m	6
7	Marsh	6	1-1, 5m	7.8
8	Marsh	7	1, 5, -2m	6
9	Marsh	8	1, 5, -2m	6.2
10	Marsh	9	1, 5, -2m	5.9
11	Marsh	10	1, 5, -2m	6.8
12	Marsh	11	1, 5, -2m	7.2
13	Marsh	12	1, 5, -2m	7.3
14	Marsh	13	1, 5, -2m	7.1
15	Marsh	14	1, 5, -2m	6.7
16	Marsh	15	1, 5, -2m	6.3
17	Marsh	16	1, 5, -2m	7.3
18	Marsh	17	1, 5, -2m	5.9
19	Salt water	NA		7, 5-8, 5
20	Rain water	NA		5, 5-5, 7

	A	B	C	D
1	Type of Mine and Fuse	Beach	Dune	Marsh
2	Fuse (ZZ42)	÷	+ ^o	÷
3	Percussion Cap	÷	+ ¹	÷
4	Detonator	÷	+	÷
5	Stock mine	÷	+ ²	÷
6	Wooden case mine	÷	+ ³	÷
7	Teller mine	+	+	+

As the Jebens (2010) data set on the left shows, pHs were only provided for marsh soils, and did not plot the functionality of mine components versus the pH. However, it would be safe to assume that the pHs will be similar for each of the three environments Jebens focused on: beach, dune, marsh. What would differ is the water table and moisture levels, and thus, redox conditions, and less so the pH. Meanwhile, the data set on the right indicates is that the Teller mines were functional regardless of environment.

Applying the vulnerability index model developed in the current Aging Study, it could be assumed that the vulnerability in general would be low for the Teller mines, but not the stock mines. However, this generalized assumption is simplistic; when examining the vulnerability index in the context of time and environment, we can better understand why the stock mines would be functional in the dunes, but not the beach or marsh, since the environment for the dunes (a ‘protective environment’) is presumably less aggressive (all times being equal). An additional hazard in this type of comparison is that different landmines were buried at different depths. However, in all cases, the metal covering the explosives was corroded but intact.

3.2. Literature related generally to the degradation of elements in the environment

While literature specific to landmine degradation is sparse, there are papers that relate generally to degradation of elements (found within landmines) in the environment generally (i.e., Fe, Mn, etc.).

One paper (Jarvis and Hedges, 1994) discusses what features of soils are responsible for the corrosion of iron, which helps explain why metallic mines in Cambodia, but not Jordan, suffer extreme corrosion. They define their terms for soil aggressiveness within their study location in **Table 4**. This paper and another (Ma et al., 2000) point to the necessity of measuring redox potential in order to see what effect it has on landmine (especially iron-based) degradation.

Table 4. Allocation of soils to aggressiveness classes (Jarvis and Hedges, 1994).

Aggressiveness class	Soil	Description
Non-aggressive chalky soils	Andover	Shallow well-drained calcareous silty soils over chalk
	Coombe	Well-drained calcareous silty soils over chalky drift or chalk
Non-aggressive other soils	Charity	Well-drained fine silty flinty soils over flinty silty drift
	Carstens	Well-drained fine silty over clayey soils over Plateau Drift and Clay-with-Flints
	Efford	Well-drained fine loamy soils over river and marine terrace gravel
	Hamble	Deep well-drained stoneless fine silty soils in brickearth
Moderately aggressive	Sonning	Well-drained flinty coarse loamy soils over river terrace gravel and drift
	Burdedon	Deep fine loamy soils with slowly permeable subsoils and slight seasonal waterlogging
	Holidays Hill	Acid sandy over clayey soils with slowly permeable subsoils and slight seasonal waterlogging
	Park Gate	Deep stoneless silty soils in brickearth affected by groundwater
	Shabbington	Deep fine loamy soils in river terrace gravel affected by groundwater
Highly aggressive	Wickham	Slowly permeable seasonally waterlogged fine loamy over clayey soils
	Windsor	Slowly permeable seasonally waterlogged clayey soils
Very highly aggressive	Fladbury	Stoneless clayey soils in alluvium affected by groundwater
	Wallasea	Deep stoneless clayey soils affected by groundwater in marine alluvium; saline groundwater
	Unripened gley soils	Soils of variable texture which may be flooded by high tides; saline groundwater

Other literature examines the long-term (thousands of years) degradation of tin and copper in soils, including the different rates of degradation of tin in soils formed from widely disparate parent materials in a similar climate (Tylecote, 1979), of particular interest to this study. An additional paper of interest (Gerwin and Baumhauer, 2000) discusses ways to quantify and create an index of soil aggressiveness (the qualities that make a soil more likely to corrode a target, whether cement or metal); **Figure 3** illustrates this process. This research touches on how clay-based, acidic soils are more aggressive (and therefore more likely to corrode metals). However, with both of these papers, the question arises: are these findings relevant to us with short-term degradation of mines (most over 60 years or less), or do they only apply to extremely old metals (2000 years old+)?

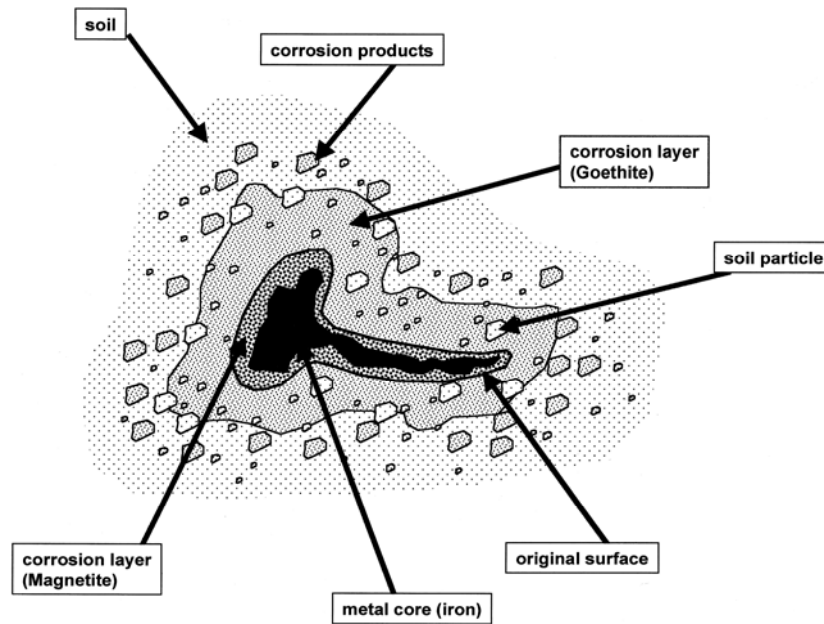


Figure 3. Corrosion process (Gerwin and Baumhauer, 2000).

3.3. Additional literature of interest

Additional literature about the context and importance of landmine clearance and degradation was found in this review. Gebrehiwot and Hamdi (2009) identify the urgent need to find cheap/economical and alternative methods for landmine removal, but did not consider landmine degradation.

Chapman (2010) summarizes why landmine abatement is hindered by the industry that has grown up around landmine removal, based on data from the K5 belt of Cambodia (one of the locations of Aging Study's current research efforts). Chapman suggests that alternative, non-profitable methods may encounter much resistance. This conceivably might include efforts like this Aging Study research for the reasons posited by Chapman.

Another paper summarizes the vast negative effects originating from landmine emplacement and explosion in various parts of the world; the author relates these effects to soils, suggesting that landmines can cause many negative effects such as: loss of access to significant portions of land; loss of both animal and plant biodiversity; degradation of soil structure (leading to erosion); toxic chemical contamination of soils; and subsequent loss of productivity from land based on all these factors, even after the landmines are removed from soils (Berhe, 2007). **Table 5** and **Figure 4** help summarize these negative impacts.

Table 5. Safe concentration of heavy metals and concentration in and around the site of landmine explosions (Berhe, 2007).

Table III. Safe concentration of some heavy metals and their concentrations in and around the site of landmine explosions. Water, food or air in parentheses represent contaminated element (Agency for Toxic Substances and Disease Registry (ATSDR), 1999a, 1999b, 1999c, 2000a, 2000b, 2003; Davies *et al.*, 1993; Aubert and Pinta, 1997; Orehovec *et al.*, 1998)

Element	Safe concentrations	Surrounding explosion site (ppm)	At the center of the explosion (ppm)
Hg	2.0 ppb (water), 1 ppm (food)	0-101	0-280
Cd	5.0 ppb (water), 15 ppm (food)	0-45	2-22
Cr	100.0 ppb (water) [Cr III and VI]	23	54
Mn	0.05 ppm (water)	88	559
Ni	0.7 ppm (water)	35	35
Pb	15.0 ppb (water), 1.5 ppb (air)	27	145

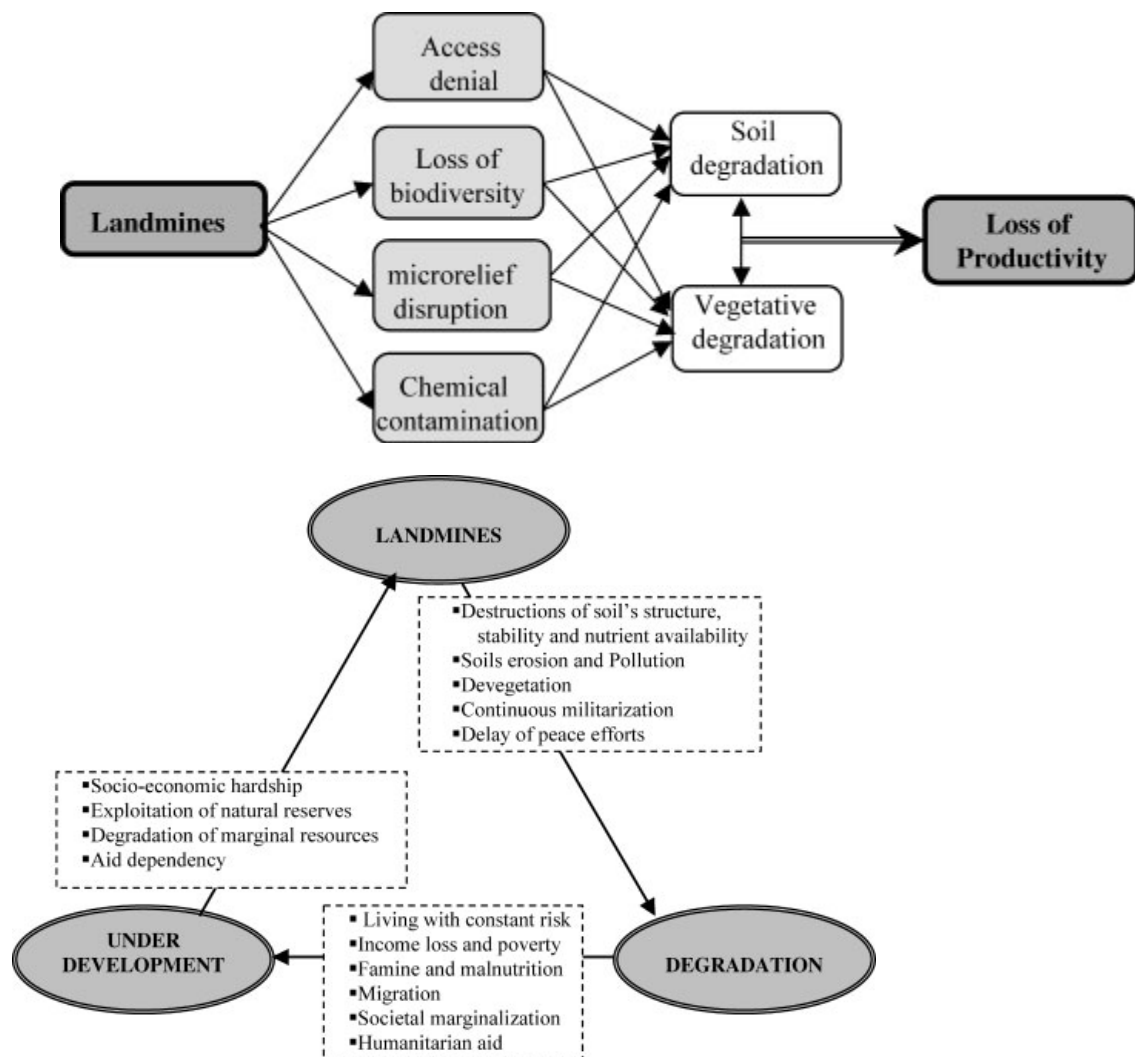


Figure 4. Model of negative effects of landmines (Berhe, 2007).

3.4. *Conclusions and implications*

The literature review indicates that very few, if any, studies similar to ours and focused on the actual degradation of landmines have existed prior to this current Aging Study, at least in the existing literature. Jebens (2010) may be the only exception.

Most research literature about emplaced landmines focuses on expensive methods to detect and remove landmines. While the need for alternative methods to removal is recognized, as well as the need for a multidisciplinary approach, very few research efforts seem to be currently applied outside the box of novel, for-profit landmine detection and removal R&D efforts.

Literature review has supported the potential equation developed in the current Aging Study research effort: $LMR = VI * E / T$ (Live Mine Risk = [Vulnerability Index * Environment] / Time).³² This equation illustrates the reality that the rate of degradation consists of three main factors, all interacting with each other in complex ways. These three are: the Vulnerability Index (VI), which is a measure of how susceptible a given landmine type (consisting of a variety of materials therein) is to degradation; in essence, this is a measure of the quality of the manufacture as well as the resistance of the materials comprising the landmine to degradation.

The second factor is time, which is crucial to understanding the rates of landmine and materials degradation. However, unless a landmine has been in a place where it is exposed to various environmental forces, it will not significantly degrade, and even under extreme conditions, it will take some time before the mine's functionality is impaired by degradation effects. Time is essential for degradation; only with the passage of time can the environmental conditions work on landmines of greatly different manufacture and VI.

This brings us to the third and perhaps most critical factor, Environment, which can include a variety of forces, from soil aggressiveness (measured in terms of redox potential, pH, acidity, etc.), soil moisture content, rainfall, heat, cold, fire, shrink/swell soils, oceanic forces (i.e., saltwater degradation), plant interferences (i.e., roots), and beyond. Human land uses should also be considered as an environmental condition; if farmers are working a mined field, their agricultural practices (tools, fertilizers, compost, grazing animals) can also accelerate landmine degradation. Some or all of these forces are directly responsible for the eventual degradation of landmines, and while the nature of the landmine components is fundamental in determining their resistance, at the same time the environment's effects are tantamount to understanding how much a landmine will resist degradation.

³² See Annex J, sections 4.1 and 5.3 for more discussion on this concept.

Literature review has also indicated that soil maps might provide an index of soil aggression, potentially one of the most important ingredients in the environmental factor portion of VI*E/T, along with water. A paper focusing on soil and soil maps in Jordan (Ziadat, 2007) tried to get at the heart of the question, asking, ‘What is the best way to get the highest resolution on a soils map without measuring every last square foot of soil?’ By comparing soil maps with pre-established criterion, the author was able to accurately derive soil characteristics, and was so able to classify multiple features of interest. It is anticipated that such mapping work can be useful in establishing soil traits such as pH, which will give future Aging Study researchers a better predictive model of soil aggressiveness. In the **Table 6**, for example, instead of field crops, future research could develop a similar approach to identifying landmine vulnerabilities.

Table 6. Rating of land characteristics, grouped by land qualities, for two land utilization types (Ziadat, 2007).

Table 1
Rating of land characteristics, grouped by land qualities, for two land utilization types

Land quality	Land characteristic	Unit	Field crops				Range crops			
			S1	S2	S3	NS	S1	S2	S3	NS
Soil	Available water holding capacity	mm/100 cm	>150	>110	>75	<75	>90	>60	>30	<30
	Soil depth	cm	>90	>60	>30	<30	>50	>35	>10	<10
Rockiness	Boulder, stone, gravel	%	<20	<40	<60	>60	<30	<60	>60	
	Rock outcrop	%	<5	<10	<20	>20	<20	<50	>50	
Erosion hazard	Rill or gully	Class ^a	1	2	3	4	1	2	3	4
	Sheet, wind or undifferentiated	Class ^a	2	3	4		2	3	4	
Topography	Slope steepness	%	<4	<8	<16	>16	<20	<40	<80	>80

^a Erosion classes: 1 = nil; 2 = slight; 3 = moderate; 4 = severe.

To conclude, literature review supports both current Aging Study research efforts and provides promising future models and data sets for refined analysis of understanding and predicting the effects of time and environment on landmines.

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Appendix 1. Glass transition temperatures of plastics.³³

Repeating Unit	T _g (°C)	T _m (°C)	Repeating Unit	T _g (°C)	T _m (°C)
Isobutyl acrylate	-24		p-Phenylene terephthalamide	345	
Isobutylene	-73		Phenylene vinylene	80	380
Isobutyl methacrylate	53		Phenyl methacrylate	110	
Isobutyl vinyl ether	-19	165	Phenyl vinyl ketone	74	
cis-Isoprene	-63	28	Potassium acrylate	194	
trans-Isoprene	-66	65	Propylene, atactic	-13	
N-Isopropylacrylamide	85-130		Propylene, isotactic	-8	176
Isopropyl acrylate, isotactic	-11	162	Propylene, syndiotactic	-8	
Isopropyl methacrylate	81		Propylene oxide	-75	66
Methacrylic acid	228		Propyl vinyl ether	-49	76
Methacrylic anhydride	159		Sodium acrylate	230	
Methacrylonitrile	120		Sodium methacrylate	310	
2-Methoxyethyl acrylate	-50		Styrene, atactic	100	
4-Methoxystyrene	113		Styrene, isotactic	100	240
Methyl acrylate	10		Tetrabromobisphenol A carbonate	157	
Methyl cellulose			Tetrafluoroethylene	117	327
Methyl glycidyl ether	-62		Tetrahydrofuran	-84	
Methyl methacrylate, atactic	105,120		Tetramethylene adipate	-118	
Methyl methacrylate, syndiotactic	115	200	Tetramethylene terephthalate	17	232
4-Methylpentene	29	250	Thio-1,4-phenylene	97	285
Methylphenylsiloxane	-86		2,2,2-Trifluoroethyl acrylate	-10	
Methylstyrene	20		Trimethylene oxide	-78	
3-Methylstyrene	97		Trimethylsilyl methacrylate	68	
4-Methylstyrene	97		2,4,6-Trimethylstyrene	162	
Methyl vinyl ether	-31	144	Vinyl acetal	355	82
Nylon 4,6 (tetramethylene adipamide)	43		Vinyl acetate	30	
Nylon 6 (-caprolactam)	52	225	Vinyl alcohol	85	220
Nylon 6,6 (hexamethylene adipamide)	50	265	Vinyl benzoate	71	
Nylon 6,9 (hexamethylene azelamide)	58		Vinyl 4-tert-butylbenzoate	101	—
Nylon 6,10 (hexamethylene sebacamide)	50	227	Vinyl butyral	322	49
Nylon 6,12 (hexamethylene dodecane-diamide)	46		Vinyl carbazole	227	320
Nylon 11 (ω-undecanamide)	42	189	Vinyl chloride	81	227
Nylon 12 (ω-dodecanamide)	41	179	Vinyl cyclohexanoate	76	
1-Octadecene	55		Vinylferrocene	189	
Octadecyl methacrylate	-100		Vinyl fluoride	41	200
1-Octene	-63		Vinyl formal	105	
Octyl methacrylate	-20		Vinylidene chloride	-18	200
Oxy-4,4'-biphenyleneoxy-1,4-phenylenesulfonyl-1,4-phenylene	230	290	Vinylidene fluoride	-40	171
Oxy-1,4-phenylenesulfonyl-1,4-phenyleneoxy-1,4-phenyleneisopropylidene-1,4-phenylene	165	190	2-Vinyl naphthalene	151	
Oxy-1,4-phenylenesulfonyl-1,4-phenylene ether	214	230	Vinyl pivalate	86	
p-Phenylene isophthalamide	225	380	Vinyl propionate	10	
			2-Vinylpyridine	104	
			4-Vinylpyridine	142	
			1-Vinyl-2-pyrrolidone	54	
			Vinyl trifluoroacetate	46	

³³ The two charts were obtained from Sigma Aldrich at the following web address:

http://www.sigmaaldrich.com/etc/medialib/docs/Aldrich/General_Information/thermal_transitions_of_homopolymers.Par.0001.File.tmp/thermal_transitions_of_homopolymers.pdf

Repeating Unit	T _g (°C)	T _m (°C)	Repeating Unit	T _g (°C)	T _m (°C)
Acenaphthylene	214		<i>N,N</i> -Dimethylacrylamide	89	
Acetaldehyde	-32	165	Dimethylaminoethyl methacrylate	19	
4-Acetoxystyrene	116		2,6-Dimethyl-1,4-phenylene oxide	167	
Acrylamide	165		Dimethylsiloxane	-127	-40
Acrylic acid	105		2,4-Dimethylstyrene	112	
Acrylonitrile, syndiotactic	125	319	2,5-Dimethylstyrene	143	
Allyl glycidyl ether	-78		3,5-Dimethylstyrene	104	
Benzyl acrylate	6		Dodecyl acrylate	-3	
Benzyl methacrylate	54		Dodecyl methacrylate	-65	
Bisphenol A- <i>alt</i> -epichlorohydrin	100		Dodecyl vinyl ether	-62	
Bisphenol A terephthalate	205		Epibromohydrin	-14	
Bisphenol carbonate	174		Epichlorohydrin	-22	
Bisphenol F carbonate	147		1,2-Epoxybutane	-70	
Bisphenol Z carbonate	175		1,2-Epoxydecane	-70	
4-Bromostyrene	118		1,2-Epoxyoctane	-67	
<i>cis</i> -Butadiene	102	1	2-Ethoxyethyl acrylate	-50	
<i>trans</i> -Butadiene	-58	148	4-Ethoxystyrene	86	
1-Butene	-24	171	Ethyl acrylate	-24	
<i>N-tert</i> -Butylacrylamide	128		Ethyl cellulose	43	
Butyl acrylate	-54		Ethylene, HDPE	-125	130
<i>sec</i> -Butyl acrylate	-26		Ethylene adipate	-46	54
<i>tert</i> -Butyl acrylate	43-107	193	Ethylene- <i>trans</i> -1,4-cyclohexyldicarboxylate	18	-
2- <i>tert</i> -Butylaminoethyl methacrylate	33		Ethylene isophthalate	51	
Butyl glycidyl ether	-79		Ethylene malonate	-29	
Butyl methacrylate	20		Ethylene 2,6-naphthalenedicarboxylate	113	
<i>tert</i> -Butyl methacrylate	118		Ethylene oxide	-66	66
4- <i>tert</i> -Butylstyrene	127		Ethylene terephthalate	72	265
<i>tert</i> -Butyl vinyl ether	88	250	2-Ethylhexyl acrylate	-50	
Butyl vinyl ether	-55	64	2-Ethylhexyl methacrylate	-10	
ϵ -Caprolactone	-60		2-Ethylhexyl vinyl ether	-66	
Cellulose nitrate	53		Ethyl methacrylate	65	
Cellulose tripropionate			Ethyl vinyl ether	-43	86
<i>cis</i> -Chlorobutadiene	-20	80	4-Fluorostyrene	95	
<i>trans</i> -Chlorobutadiene	-40	101	Formaldehyde	-82	181
2-Chlorostyrene	119		Hexadecyl acrylate	35	
3-Chlorostyrene	90		Hexadecyl methacrylate	15	
4-Chlorostyrene	110		Hexyl acrylate	57	
Chlorotrifluoroethylene	52	214	Hexyl methacrylate	-5	
2-Cyanoethyl acrylate	4		2-Hydropropyl methacrylate	76	
Cyclohexyl acrylate	19		Hydroquinone- <i>alt</i> -epichlorohydrin	60	
Cyclohexyl methacrylate	92		2-Hydroxyethyl methacrylate	57	
Cyclohexyl vinyl ether	81		Indene	85	
2,6-Dichlorostyrene	167		Isobornyl acrylate	94	
Diethylaminoethyl methacrylate	20		Isobornyl methacrylate	110	

Appendix 2. Theoretical and experimental IR data for TNT (Alzate et al., 2006).

ν	C_s conformer		C_1 conformer		IR experimental	Assignments
	Frequencies (cm ⁻¹)	IR intensities	Frequencies (cm ⁻¹)	IR intensities		
1	43	0	41	0		4-NO ₂ bend oop twisting
2	46	0	44	0		2,6-NO ₂ bend oop twisting
3	53	0	57	0		2,6 NO ₂ , CH ₃ bend oop wagging
4	91	6	66	0		2,6 NO ₂ , CH ₃ bend oop wagging
5	116	5	78	4		C-C ring, CH ₃ bend oop wagging
6	146	3	117	6		2,4,6-NO ₂ bend in plane twisting CH ₃ bend oop twisting
7	164	0	152	2		CH ₃ methyl bend oop twisting
8	180	0	176	5		CH ring bend oop twisting
9	182	6	180	0		2,6-NO ₂ bend in plane rocking
10	285	3	281	2		C-C ring, CH ₃ bend oop wagging
11	313	0	314	0		2,6 NO ₂ , CH ₃ bend in plane rocking
12	318	0	317	0		C-N, ring bend in plane scissoring
13	353	3	350	1		Ring bend in plane scissoring
14	357	2	357	3		CH ring bend in plane rocking
15	375	0	393	2		CH ring bend oop twisting, CH ₃ bend in plane rocking
16	466	2	410	1		CH ring bend oop wagging
17	474	0	500	5		CH ring bend oop twisting, CH ₃ bend in plane rocking
18	532	2	541	2		4C-N bend oop wagging
19	546	2	579	0	586	4C-N bend in plane scissoring, ring
20	648	5	692	21	639	2,6 C-N, bend oop twisting, CH ring bend in plane rocking
21	668	0	590	0	680	CH ring bend oop wagging
22	705	19	705	8	704	4 C-N, CH ring bend oop wagging
23	729	21	732	26	723	2,4,6 C-N, CH ring bend oop wagging
24	738	49	741	37	731	2,6 NO ₂ , CH ring bend in plane scissoring
25	781	6	789	3		2,4,6 NO ₂ , CH ring bend oop wagging
26	785	0	774	5		2,6 NO ₂ , CH ring bend oop twisting
27	806	15	806	14	793	CH ring bend in plane scissoring, C-CH ₃ stretching
28	844	2	844	2		2,4,6-NO ₂ bend in plane scissoring
29	918	34	916	38	907-919	CH bend in plane, 2,6 NO ₂ in plane scissoring, C-N stretch
30	940	40	940	21	938	CH ring bend oop wagging, CN stretch
31	947	18	943	36		CH ring bend oop wagging, CN stretch
32	955	1	954	1		CH ring bend oop twisting
33	1047	2	1040	2	1034	CH ring bend in plane rocking CH ₃ deformation
34	1049	1	1056	2		CH ₃ bend oop twisting
35	1097	51	1098	46	1084	CH ring bend in plane scissoring
36	1179	13	1179	15	1170	C-C, CH ring bend in plane, 2,4,6 CN, C-CH ₃ stretch
37	1219	0	1217	3		C-C, CH ring bend in plane scissoring, C-CH ₃ stretch
38	1220	13	1223	10	1200	CH ring bend in plane rocking
39	1343	2	1343	2	1306	Ring stretching
40	1370	358	1370	356	1350	4 NO ₂ , C-N stretch symmetric
41	1380	316	1383	311		2,6 NO ₂ , C-N stretch symmetric
42	1389	2	1393	15		2,4,6 NO ₂ , C-N stretch symmetric
43	1419	11	1417	11	1382	CH ₃ stretch symmetric (umbrella)
44	1421	6	1427	7	1404	C-C ring stretch, CH ring bend in plane rocking
45	1475	5	1470	4	1445	C-C ring stretch, CH ring bend in plane scissoring
46	1476	9	1483	10		CH ₃ deformation
47	1498	10	1500	8	1468	CH ₃ bend in plane scissoring
48	1589	192	1589	185	1533	4 NO ₂ , ring stretch asymmetric
49	1602	374	1603	123	1545	2,6 NO ₂ , ring stretch asymmetric
50	1603	6	1605	343	1551	2,4,6 NO ₂ , ring stretch asymmetric
51	1646	139	1644	128	1608	2,4,6 NO ₂ , ring stretch asymmetric
52	1651	140	1649	87	1617	2,6 NO ₂ , ring stretch asymmetric
53	3064	1	3056	0	2882	CH ₃ stretch symmetric
54	3128	5	3122	1	2919	CH ₃ stretch asymmetric
55	3155	4	3184	3	2956	CH ₃ stretch asymmetric
56	3233	15	3231	20	3070	CH ring stretch symmetric
57	3233	31	3233	22	3098	CH ring stretch asymmetric

D: Cambodia Mines

PMD-6 ANTI-PERSONNEL MINE



The original appearance of the PMD-6



A typical recovery site (mine 6)



None of the wood casing remains from mine 6. There is a clear break between the fuze and the TNT block (indicated by the red arrow); this was filled with mud.



Every PMD-6 mine recovered had a break between the fuze and the charge



Remnants of the wooden casing are visible once the TNT charge has been removed



The end of the TNT block, looking into the mouth of the detonator tube



The TNT block broken open to show the corroded detonator tube



The retaining pin of fuze 8 was almost rusted through, but the striker was seized



The retaining pin of fuze 6 was in relatively good condition



The mechanical components of fuze 6 might have been operational, but it is unlikely that the stab receptor would have functioned

PMD-6: SUMMARY OF FINDINGS

- The wooden case of every PMD-6 had rotted, with only small remnants found. Since the casing forms part of the initiation system (by pushing the retaining pin out to release the striker), these mines could no longer function as designed.
- The MUV-2 fuze components were intact, but were seized and had to be separated using force. The stab receptors were in poor condition and were probably not functional.
- The upper section of the aluminum detonator tube had corroded away, leaving a break of approximately 5-10 mm between the fuze and the main charge. This gap was filled with mud, which would probably have prevented the flash from the stab-receptor from initiating the detonator.
- Burning tests on two charges resulted in eventual detonation, indicating that the primary explosive within the detonator was still viable, and capable of initiating the main TNT charge.

CONCLUSIONS

- All of the PMD-6 mines examined showed multiple causes of failure, namely:
 - Absence of the casing as part of the initiation mechanism;
 - Seizure of mechanical fuze components;
 - Inactive stab-receptors (subject to confirmation);
 - Interruption of the initiation train.
- The combination of these effects would make it impossible for any of these mines to function as designed. Other PMD-6 mines buried in similar conditions for similar periods are also unlikely to function.

- The TNT charges are still hazardous, particularly since they contain embedded detonators with viable primary explosive. These could be initiated if set alight or subjected to substantial impact.

PMN ANTI-PERSONNEL MINE



The original appearance of the PMN



A typical recovery site (mine 12)



A close-up showing how the roots have grown around mine 12



The PMN with detonator removed; in some mines the detonator could not be extracted



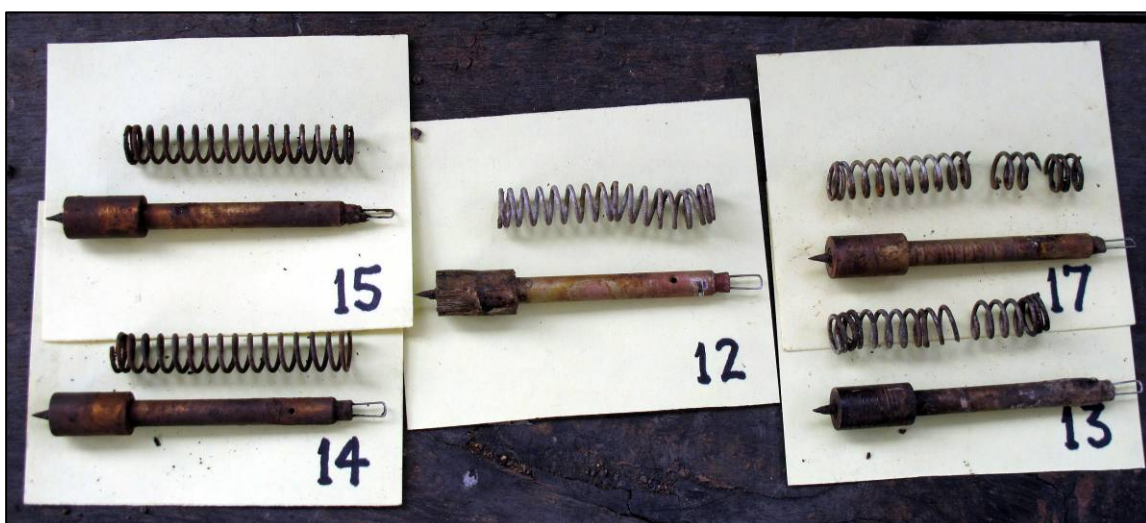
Some of the rubber covers were damaged, allowing water to enter the mine body



In some cases, soil had almost filled the void beneath the pressure plate



Components of mine 13 with TNT charge still in place within the body. The mine may have been functional despite the striker spring being badly deteriorated



Strikers and springs showed substantial variation in the degree of degradation



Striker 12 was badly corroded and seized; this would have prevented operation



Most detonator capsules were functional, confirmed by explosive testing

PMN: SUMMARY OF FINDINGS

- The steel bands securing the rubber covers were badly rusted in all examples; many were at or near the point of failure. This is known to reduce the detection signature.
- Rubber covers had deteriorated and hardened; some, but not all, were breached. This does not prevent the mine from working, but does allow water into the fuze mechanism.
- The main effect of water inside the mine is to cause the springs to rust. The striker spring is most critical to failure; however, deterioration of the plunger spring could potentially lead to a decrease in operating pressure.
- As noted in the previous report, springs in contact with alloy strikers appear to deteriorate more quickly than those around steel strikers.
- Most strikers were in operational condition, but one had deteriorated badly and was seized into its channel. This would have caused the initiation mechanism to fail.
- TNT charges were in good condition and detonators appeared to be functional. Two detonator tests (using a PMN fuze mechanism in good condition) resulted in detonation.

CONCLUSIONS

- All of the PMN mines examined showed significant deterioration, but some still appeared to be functional while others clearly were not.
- The most common cause of failure is deterioration of the striker spring, which begins when water enters the mine and eventually results in disintegration. Other likely causes of failure include:
 - Degradation and seizing of the striker;
 - Prevention of operation due to silt build up in cavities.
- Explosive components appear to out-live the fuze mechanism.
- These findings are consistent with those from the first phase of the study.

PMN-2 ANTI-PERSONNEL MINE



The original appearance of the PMN-2



A PMN-2 recovery site (mine 18)



Deterioration of the rubber
pressure plate cover



The mine's base, with booster plug
and booster capsule removed



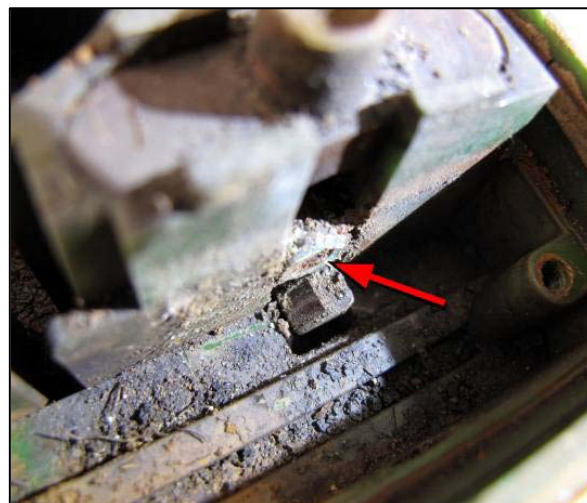
The mine cleaned to show the extent
of the rubber and casing degradation



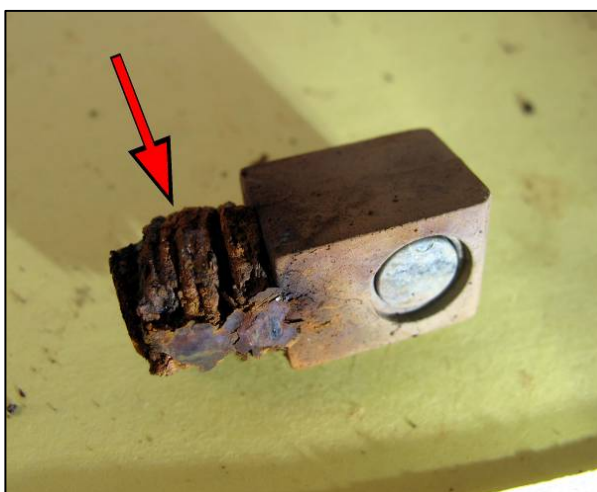
Removal of the securing ring reveals the penetration
of soil and roots



Top plate removed to show the main charge (to the left) which is in good condition. The fuze mechanism (to the right) has degraded



A close-up showing the end of the striker. The arrow indicates where the firing pin should be, but this has rusted away completely



The slider containing the detonator. The arrow indicates the spring, which should move the detonator into line with the striker as the mine is actuated; this spring is no longer functional



Components of the fuze mechanism, showing that all springs were badly rusted. The plunger (top left) and striker (below) were firmly seized into their channels

PMN-2: SUMMARY OF FINDINGS

- The rubber pressure plate covers were badly perished, with large sections missing. In several examples, the top edge of the plastic casing was also split. This damage would not prevent the mine from working, but does allow water into the fuze mechanism.
- The main effect of water inside the mine is to cause the springs to rust. The striker spring and detonator slider spring are both critical to operation and their deterioration can cause failure.

- Deterioration of the plunger springs could potentially lead to a decrease in operating pressure, but appears to be offset by seizing of the plunger itself.
- In every PMN-2 examined, the striker was seized into its channel; this appears to be caused by a build-up of corrosion, leading to expansion beneath the metallic plating.
- In several examples, the steel firing pin (which is inset into the end of the alloy striker) had rusted away completely, leaving the striker with a flat end.
- In all examples, the explosive charges (RDX/TNT) and boosters were in good condition and detonators appeared to be functional. However, the detonator is held out of line until the mine is actuated, and relies on the slider spring to bring it into line.

CONCLUSIONS

- All of the PMN-2 mines examined showed significant deterioration and none appeared to be capable of functioning.
- The most common cause of failure is seizing of the striker into its channel. However, some mines showed multiple points of failure, including:
 - Absence of the firing pin;
 - Seizure of the detonator slider and spring;
 - Seizure of the plunger.
- Explosive components appear to be stable and functional.
- These findings are consistent with those from the first phase of the study.

TYPE 72 ANTI-PERSONNEL MINE



The appearance of the Type 72 when new



A typical recovery site (mine 2)



A closer view of the recovery site, with the edge of mine 2 just visible



The soil type, burial depth and appearance of the mine are typical of the Type 72s recovered



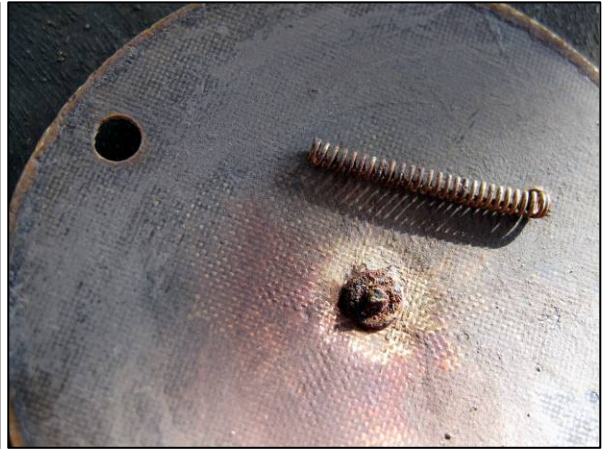
Mine 3 was unusual because it was found buried upside down



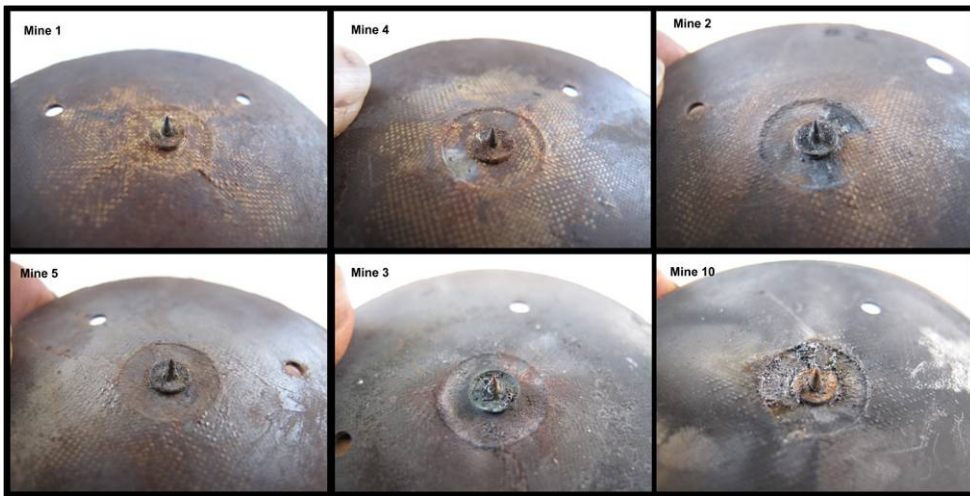
The rubber cover on mine 3 was better preserved than most



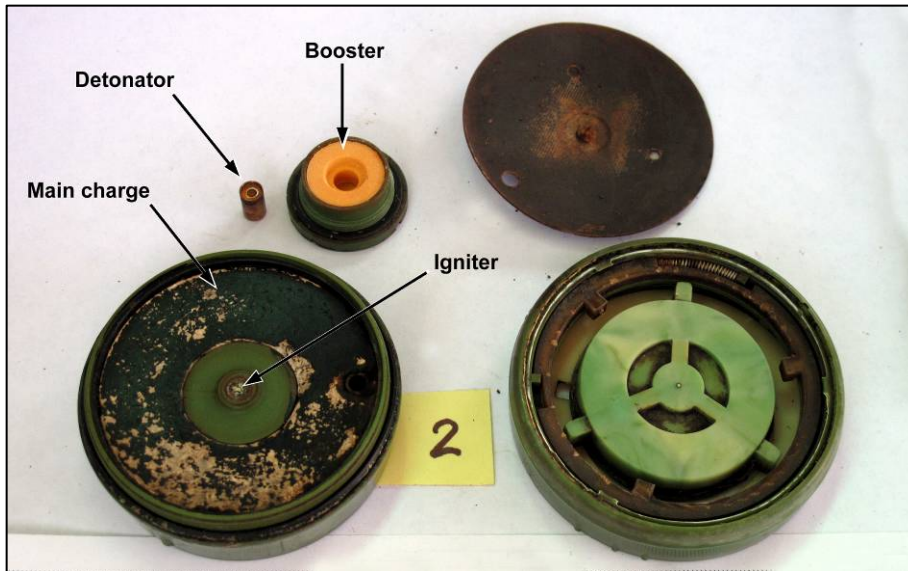
With the rubber cover missing, the Type 72 is penetrated by water and soil



The tip of this firing pin has rusted away, leaving the mine unable to function



Most of the mines recovered had firing pins in reasonable condition, though superficial rusting had rounded off the ends, making them less likely to fire the igniter



The main charge, booster and detonator appeared to be functional in most of the mines recovered. However, some of the igniters had deteriorated.

Function tests using firing pins in good condition confirmed that some igniters were no longer operational

TYPE 72: SUMMARY OF FINDINGS

- The rubber pressure plate cover was badly perished or absent in all of the mines examined. In every case, this had allowed water and soil to penetrate the mine body.
- Without the smooth green rubber cover, the appearance of aged Type 72 mines is quite different, and may not be recognizable to people who have only seen it in new condition.
- The primary effect of water inside the mine is to rust the mild steel firing pin. Initially, this causes the tip to become rounded and therefore shorter, which makes it far less likely to fire the igniter.
- The likelihood of initiation continues to fall as the mass of steel within the firing pin decreases further. This, combined with rusting of the helical arming spring, may also make the mine difficult or impossible to locate using a metal detector.
- Most of the Type 72 mines examined had fuzes that were already actuated (shown primarily by the inversion of the Belleville spring), but the mines had not detonated.
- Most explosive components remained in reasonable condition and appeared to be functional. However, some of the stab-sensitive igniters were no longer operational.

CONCLUSIONS

- Breaching of the thin rubber cover means that all Type 72s examined had significant levels of deterioration. However, some still appeared to be capable of functioning.
- The most common cause of failure is rusting of the firing pin. Degradation of the igniter may also cause failure, particularly in conjunction with a short, rounded firing pin.

- With the rubber cover missing, the mine can be difficult to recognize; this has important implications for mine risk education and deminer training.
- Older mines with minimal metallic content may require alternative means of detection.
- A complete explosive train (detonator, booster and main charge) may remain even when the fuze is non-functional. This means the mine is still hazardous.
- These findings are consistent with those from the first phase of the study.

E: Jordan Mines

M14 ANTI-PERSONNEL MINE



Most of the M14s were flush with the ground level so that the pressure plate was exposed



Soil was carefully removed to expose the mine, with samples taken from close to the body



The plastic casings had faded to varying degrees, but were still intact and robust



Despite long-term exposure to the sun, the upper surfaces showed very little deterioration



The bases were in good condition, with markings still legible. Rubber seals had hardened



A number of M14 bases showed deterioration of the plastic that had been in contact with the nylon cord.

This appears to be a surface effect, but is nevertheless hard to explain



The M14 detonator assembly consists of a copper capsule set into a plastic housing



With the plastic housing removed, all detonators appeared to be in a functional condition



In all cases, the main charge of Tetryl was in good condition and fully functional



The Belleville springs (used to drive the firing Pin) showed no signs of deterioration



The mild steel firing pins had rusted to varying degrees, but most showed only superficial corrosion

M14: SUMMARY OF FINDINGS

- After long-term exposure to hot conditions and bright sunlight, the M14 plastic casings showed few signs of deterioration, although the color had faded in some places
- The stab-sensitive detonators and main explosive charges appeared to be in good condition and functional, with only slight superficial degradation
- The material used for the Belleville spring appears to be highly resistant to deterioration
- The mild steel firing pins had rusted to varying degrees, though most of the corrosion appeared to be superficial and unlikely to affect performance
- Overall, there was little evidence of water or silt ingress in these mines. The firing pin is probably the most vulnerable component, yet even these were relatively unaffected by aging. The mines examined were probably capable of functioning as intended and, given the slow rate of deterioration, could be expected to remain so for many more years

M15 ANTI-TANK MINE



An overview of the area from which an M15 mine was recovered. Note that the vegetation has been cleared from the area around the mine and that the ground has been disturbed while checking for anti-personnel mines



Two M15 mines were recovered, both were laid flush with the surface in well-drained soil



The mine was uncovered and soil samples taken from ground in contact with the side of the mine



Both mines were in exceptionally good condition, with paint still covering most of the body



Markings were still clearly visible on the base, indicating that the mines dated from 1954



The side of the mine was the area most affected by rust, but neither of the casings was penetrated.
The filler plug appeared to be particularly vulnerable

M15: SUMMARY OF FINDINGS

- The M15 mines were in good condition externally, with only superficial rust
- Rust was confined mainly to the side of the mine, but had not penetrated the casing. Very little rust was visible on the top surface or base, other than the wire carrying handle
- The steel fuze cap could not be unscrewed from the central well of the pressure plate using the available resources. Although little corrosion was visible, both assemblies are steel and had rusted together enough to prevent movement
- Examination of the internal components could not be conducted; however, based on the external condition, it is highly likely that the fuzes were in good condition and that the mines were fully functional
- There is no evidence that water had penetrated the casings of these mines. Based on the rate of degradation seen here, these mines could remain intact for many more years.

M19 ANTI-TANK MINE



An overview of the area from which an M19 mine was recovered. Note that the vegetation has been cleared from the area around the mine and that the ground surrounding the tape and pickets has been disturbed while checking for anti-personnel mines



Most of the M19 mines were laid flush with the surface of the ground



The mines were easily removed. The casings showed little sign of external deterioration



Most fuze assemblies were easily detached from the mine bodies



Every M19 seen in this area appeared to be in equally good condition



The mine casings, manufactured in 1964, showed no significant signs of deterioration



Base plate removed to expose the main charge and booster; both were in excellent condition



This large Belleville spring raises the operating pressure over 100 kg; it appears to be as new



The small Belleville spring and stainless steel striker were in perfect condition



The detonator housing incorporates a copper detonator capsule



Detonators were in excellent condition, with minimal surface degradation

M19: SUMMARY OF FINDINGS

- The M19 mines casings were in excellent condition, with no visible deterioration
- Rubber seals between the fuze assembly and body had hardened, but there was no indication that water had penetrated the mines.
- All explosive components appeared to be in good condition and fully functional.
- The main Belleville spring, responsible for maintaining an adequate operating pressure, showed no sign of deterioration.
- The small firing Belleville spring was also unaffected.
- The firing pin in the M19 is stainless steel and therefore highly resistant to corrosion.
- Examination suggests that these M19 mines would remain functional for many years to come.
- The most likely failure mechanism in the long term is the eventual breakdown of the rubber seals, leading to the ingress of water and silt.

M35 ANTI-PERSONNEL MINE



An overview of the area from which the M35 mines were recovered. Note that the vegetation has been cleared from the foreground and that mine is not yet visible because it is beneath the surface.

These areas of grassland are prone to occasional fires, which can affect mines on or near the surface



This M35 (No.1) was protruding slightly from the surface, and has a damaged fuze



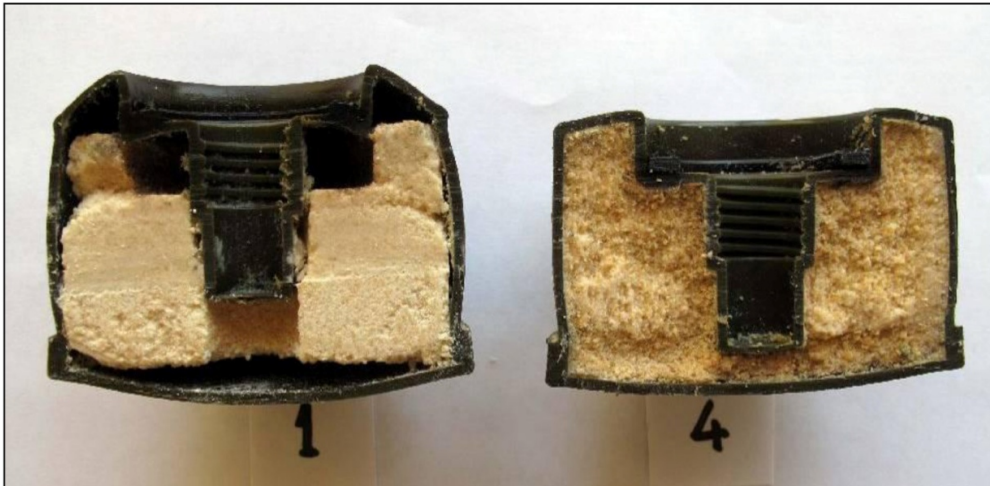
The casing of this mine is distorted, probably from expansion during grass fires



This M35 mine, located well beneath the surface, shows very little distortion



The casing is in good condition, with markings on the base indicating manufacture in 1960



Sections through two mine bodies. Mine 1 has large voids where the casing has expanded away from the explosive. The explosive (TNT and potassium nitrate mixture) is crumbly in both mines



Most detonator and igniter capsules appeared to be functional (scale in mm)



The spring wires in the foreground serve as strikers and firing pins; most were in good condition



Comparison of the striker wires in position within the fuze housings. Wires in the left hand fuze show substantial corrosion, with one having collapsed completely. Those in the other three fuzes have only superficial rust and retain their functionality.

M35: SUMMARY OF FINDINGS

- Of the four M35 mines examined, three appeared to be functional.
- The mine (No. 1) that showed the greatest deterioration was protruding from the ground
- Mine No. 1 had a distorted casing and a damaged fuze which had permitted the ingress of water. Bulged M35 mines are also seen in parts of Africa.
- Despite being misshapen, all of the plastic casings maintained their integrity.
- The explosive charges were crumbly, but it is not known whether this would affect performance.
- Most detonator and igniter capsules showed surface degradation, but appeared functional.
- The spring striker wires were functional in most mines. Both wires in mine No.1 were heavily corroded due to the ingress of water; this would have caused the fuze to fail.
- Examination suggests that buried M35 mines would remain functional for many years to come.
- The most likely failure mechanism in the long term is deterioration of striker wires, detonator and igniters when water penetrates the fuze.
- Fuzes on or near the surface are prone to fire damage, which will hasten the degradation process.

BRITISH Mk 2 ANTI-PERSONNEL and Mk 5 ANTI-TANK MINES



An overview of the border area where a number of Mk2 and Mk 5 mines were located. All mines were on the surface and fully exposed to the environment



The Mk 2 dates from the Second World War and is basically a large fragmentation grenade in a steel pot. Tripwires were no longer present, so the mines could not function as designed. The cocked strikers and rusty fly-off levers make these mines too dangerous to defuze, recover or dismantle



All Mk 5 mines were found on the surface, although they should have been buried



This mine had a cap in place covering the fuze, which was kept in excellent condition



The base of the mine, with the removed fuze to the right. The mine is dated 1943



The base of the mine had become detached, with the explosive charge crumbling inside



The main charge of TNT appears to have repeatedly melted and recrystallized, leading to expansion and disintegration of the original casting. Expansion of the explosive may have caused the bases to separate



The two fuzes examined were in exceptionally good condition and appeared to be fully functional. The large tetryl booster at the base of the fuze (seen separated on the right of this image) was in perfect condition

Mk 2: SUMMARY OF FINDINGS

- The fly-off lever was heavily rusted, posing a potential danger that, with little stimulus, it might release the striker and detonate the mine.
- Mk 2 mines are therefore considered too unpredictable to examine in detail, however: tripwires were absent, so the mines could not function as designed.
- All visible external steel components were heavily rusted.
- The condition of strikers and springs could not be established but, based on findings from the Mk 5 mines, might still be functional.
- Although incapable of functioning as intended by tripwire actuation, these mines may still pose a significant threat if disturbed. The most likely failure mechanism is that the strikers, springs and retainers seize together to prevent operation of the fuzing mechanism.

Mk 5: SUMMARY OF FINDINGS

- The external steel surfaces were rusted, but not excessively.
- The alloy fuze body showed only slight deterioration.
- The simple fuze mechanism (spring-loaded striker retained by a shear pin) was functional.
- The booster charge was dry and in perfect condition, suggesting that the detonator assembly was probably in a similar condition.
- The main explosive charge appeared to have melted and recrystallized, resulting in expansion.
- Expansion of the main charge had created a friable mass and forced the base plate off the mine unlike many other mines showing the effects of aging, the Mk 5s appeared to have fully functional fuzes, but main charges that were unlikely to sustain complete detonation.

F: Falkland Island Mines

THE MINE EXTRACTION PROCESS



Overview of the Surf Bay minefield



A clearance lane, with located mines to the right



Beginning extraction of an SB-81 AT mine



Turf was cut from above the mine



Cut turf was removed in blocks to expose the entire body of the mine



With the mine extracted, the underlying ground was photographed and examined



Extracted mines were disarmed immediately



A wet ditch containing a number of mines



An SB-33 AP mine under water



An SB-33 in relatively dry ground



The extraction process for the SB-33 was similar to that used for the SB-81



Disarming the SB-33 by unscrewing the detonator assembly from the base of the mine

EXAMINATION OF THE P4B



Figure 1



Figure 2

Most of the P4B mines examined showed little obvious sign of external degradation, with both the colour and the texture of the plastic casing appearing virtually 'as new' (Figure 1). However, the condition of some mines suggests that this initial visual impression may be misleading, and that all of the plastic casings are now beginning to deteriorate.

Many had some degree of root penetration between the underside of the fuze (Figure 2) and the mine body. This type of growth would not affect performance, although it is possible that further enlargement of the roots might eventually force the two assemblies apart, resulting in malfunction.



Figure 3

Throughout the course of the clearance operation, all but one of the P4B mines examined had the red lacquered lead foil present in fuze well. As the fuze assembly is fitted, this foil ruptures in unpredictable patterns (Figure 3). The shape of the ruptured foil is known to affect the return on short-wave radar and may also affect the signature with some metal detectors.



Figure 4



Figure 5

The P4B pressure plate shown in Figures 4 and 5 shows the type of long-term deterioration expected in ABS plastic. Increasing brittleness has caused fine cracks where the plastic is under stress; this has led to eventual failure, permitting the ingress of water. In most samples examined, cracking was not immediately visible; however, it is evident that the plastic is becoming more brittle and that all casings would eventually reach this stage. Previous studies have shown that such deterioration accelerates, since the effects (such as increasing the exposed surface area) make the material even more vulnerable to further degradation. Extensive tests would be required in order to assess the rate of degradation.



Figure 6

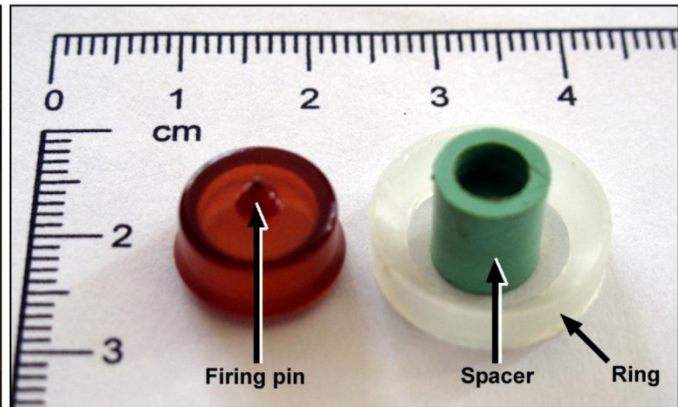


Figure 7

Even where water had penetrated the fuze assembly, the firing spring (Figure 6) was in remarkably good condition and remained fully functional. This was surprising, although, had the mines been nearer the coast, salt-water would probably have caused more extensive rusting. This would further degrade the detection signal from the small metallic mass.

It is important to note that the P4B can function regardless of the spring's condition. The firing pin is made from polymethylacrylate plastic, which is unlikely to deteriorate significantly within the foreseeable future. It is forced through a polythene ring by a spacer and this action alone may be sufficient to cause initiation without the additional impetus of the spring. These plastic components are shown in Figure 7.



Figure 8



Figure 9

The detonator assembly is bonded into the fuze body and has to be cut from the mine, as shown in Figure 8. The stab-sensitive receptor in the centre is covered by a thin plastic film (seen here having been cut using a scalpel) to keep it dry. A similar assembly, shown in Figure 9, was full of water.



Figure 10

The presence of water might prevent the stab receptor from initiating, since water-soluble compounds are used within the composition. This is likely to be the primary cause of failure for P4B mines in the near term.

As expected, the pressed TNT charges (Figure 10) were in good condition, despite many being wet. TNT is relatively stable, especially when protected from sunlight. This High Explosive (HE) content is likely to remain functional for the foreseeable future.

Conclusions

1. Most of the P4B mines examined appeared to be fully functional.
2. Deterioration of the plastic casings has begun, but – in most instances - is progressing at a far slower rate than expected. Most mines have retained their structural integrity.
3. The ingress of water into the fuze assembly has caused only minor deterioration of the striker springs. This will not significantly affect the detection signature or the mine's ability to function.
4. The ingress of water into the detonator assembly may render the mine inoperative; this would need to be confirmed by testing.
5. The lead foil was present in all but one of the mines examined. The manner in which the foil splits (when the fuze assembly is fitted) may affect the detection characteristics of the mine. Determining this would require additional trials.
6. The TNT HE content is stable and well preserved.

EXAMINATION OF THE SB-33



Figure 1



Figure 2

Seventeen SB-33 mines were recovered from a mixture of dry and wet sites (Figures 1 and 2). None of the SB-33 mines examined showed signs of significant external degradation, other than a notable increase in the profile of the rubber pressure plate; this is clear from Figures 3 and 4.



Figure 3: An SB-33 recovered from the Falklands; note the domed profile of the pressure plate



Figure 4: The normal appearance of the SB-33, with a relatively flat pressure plate

The casing of the SB-33 is made from glass-reinforced polycarbonate and showed no indication of deterioration whatsoever. However, all of the recovered mines had been buried, and it is probable that the casings and rubber pressure plates would degrade more quickly after prolonged exposure to the sunlight.

Expansion of the rubber appears to be due to the material softening when wet, although it continued to be waterproof. As the rubber dried, the height of the dome reduced noticeably, but not to the original profile.

Examination of the casing and pressure plate showed that the upper sections of all of the mines had remained watertight. Where water had penetrated, this appeared to be because the detonator plug (to the left in Figure 3) had not been tightened sufficiently.



Figure 5



Figure 6

Mines were disarmed by unscrewing the detonator assembly from the base well (Figure 5); in most cases, this plug had been fitted tightly. Once disarmed, the two halves of the mine were unscrewed using a chain wrench (Figure 6) to access the internal components and main charge.



Figure 7

Figure 7 shows a recovered SB-33 disassembled. Most of the clear plastic internal fuze components are made from polycarbonate, and are therefore extremely strong.

Some casings were made from olive green plastic; others (including this one) were grey and merely painted green on the outside.

None of the internal components showed any mechanical damage. The main charge (RDX/HMX) was often cracked, but this would not affect performance.

Although the mines were generally well sealed, several were damp inside. In many cases this had caused very minor rusting of the striker spring (which is made from spring steel 'piano wire'). This superficial corrosion would have no effect on the performance of the mechanism, nor would it effect the detectability of the mine.

The firing pin is made from stainless steel and none of those examined showed any significant degree of corrosion.

Most of the aluminium detonator capsules were in good, functional condition (Figures 8 and 9), but some did show significant signs of corrosion; see Figures 10 and 11.



Figure 8: Most detonator assemblies were in very good condition



Figure 9: The end seals of these detonator capsules show no signs of deterioration



Figure 10: Some detonator capsules did show significant signs of degradation



Figure 11: The yellow seal on the stab receptor appears to have been breached

There was obvious degradation where detonator capsules had been exposed to water for prolonged periods. It is likely that this had breached the seals of the capsule, particularly the thin yellow membrane covering the stab receptor. This is significant because the stab-receptive composition is likely to be affected by water, which may cause the mine to malfunction.

Only one of the recovered SB-33 mines contained a significant quantity of water; this was caused by the detonator plug not being screwed into place sufficiently tightly. The most obvious result of the water ingress was the disintegration of the striker spring, which would probably prevent the mine's fuze mechanism from actuating and might also make the mine more difficult to detect. The detonator capsule was also substantially corroded and possibly non-functional.

The badly corroded mine (shown in Figure 12) demonstrates the longer-term fate of all SB-33 mines, as rubber seals gradually deteriorate and permit water to enter the mine.



Figure 12: Inside an SB-33 which had been penetrated by water. The most likely cause of failure would be the disintegration of the striker spring, although degradation of the detonator capsule might also prevent the mine from operating. Note that the stainless steel firing pin is virtually unaffected

Conclusions

1. Most of the SB-33 mines examined appeared to be fully functional.
2. The rubber pressure plates were distorted where the material appeared to have softened; this probably indicates the beginning of degradation that would eventually lead to failure.
3. Deterioration of the rigid mine casings was minimal and all of the mines examined retained their structural integrity.
4. Minor dampness inside the mines has caused only minor deterioration of the striker springs. This will not significantly affect the detection signature or the mine's ability to function.
5. Degradation of the detonator assembly, due to dampness, may render the mine inoperative; this would need to be confirmed by testing.
6. The HE charges are well preserved, despite some being cracked.
7. Where water had penetrated a mine, the striker spring and detonator capsule showed substantial deterioration; this would almost certainly have prevented it from functioning. In the long term, this is what could be expected to happen to all SB-33 mines in the Falklands.

EXAMINATION OF THE SB-81



Figure 1



Figure 2

Fifteen SB-81 Anti-Tank (AT) mines were recovered from a mixture of dry and wet sites (Figures 1 and 2). None of these mines showed signs of significant external degradation; in fact, their appearance was virtually 'as new', as shown in Figures 3 and 4.



Figure 3: An SB-81 recovered from the Falklands



Figure 4: Base view of the SB-81

The casing of the SB-81 is made from polycarbonate and showed no indication of deterioration whatsoever. Even the pressure plate, which is made from a polyester elastomer, appeared to be in pristine condition.

All of the mines examined had been buried in the ground and were not, therefore, exposed to sunlight. Polycarbonate is known to become brittle after prolonged exposure to sunlight, so it is probable that exposed mines would show more evidence of degradation.

Examination of the casing and pressure plate showed that all of the mines had remained watertight. Where there was evidence of moisture on the inside, as with the SB-33, this appeared to be because the detonator plug (shown in Figure 4) had not been tightened sufficiently.



Figure 5



Figure 6

With the halves of the casing separated, the internal components could be examined. Figure 5 shows upper section of the mine with the pressure plate removed to reveal the top of the fuze assembly. The seal around the edge of the pressure plate is critical to the pneumatic function of the fuze; this is a common point of failure among Italian AT mines. Although small roots were present on the outside (Figure 6) all seals were intact.



Figure 7

Figure 7 shows the major components of the fuze mechanism. The fuze is similar to that used in the SB-33, with most of the clear plastic internal fuze components made from polycarbonate.

Not only were the components in perfect condition, but the thin layer of grease applied during manufacture was also present.

As with the SB-33 mines, the SB-81s were generally well sealed, but several were damp inside. In many cases this had caused very minor rusting of the striker spring (which is made from spring steel 'piano wire'). This superficial corrosion would have no effect on the performance of the mechanism, nor would it effect the detectability of the mine. The firing pin is made from stainless steel and none of those examined showed any corrosion.

The main charge (approximately 2 kg of TNT/RDX/HMX) is encapsulated in plastic, while the booster (approximately 140 g of RDX/HMX/wax) is in the form of a pressed disc. These are shown in Figure 8. Removal of the plastic showed the main charge to be in perfect condition (Figure 9).



Figure 8: The main charge and booster

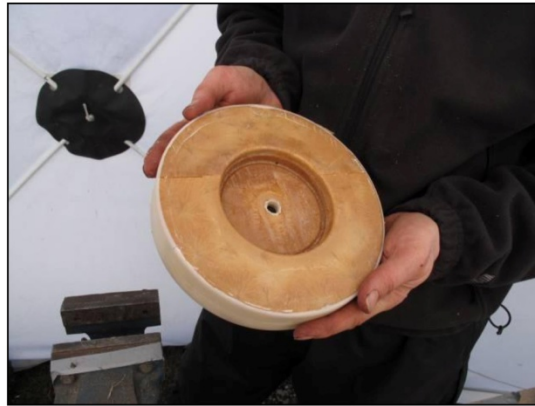


Figure 9: The main charge casting



Figure 10: Some detonator capsules showed significant signs of degradation



Figure 11: The yellow seal on the stab receptor appears to have been breached

The SB-81 uses the same detonator capsule as the SB-33, albeit in a different holder (Figure 10). Most were in good condition, but some, such as the one shown in Figure 11, showed obvious signs of degradation where they had become damp. It is possible that, in some cases, this had breached the seals of the capsule, particularly the thin yellow membrane covering the stab receptor. This is significant because the stab-receptive composition is likely to be affected by water, which may cause the mine to malfunction.

Since the casings have endured so well, the deterioration of detonator capsules represents the most likely cause of failure within the next few years. In the longer term, more water can be expected to enter the mines as rubber seals gradually deteriorate. In addition to affecting the detonators, this will also corrode the striker springs and cause failure of the fuze mechanism.

Where mines are exposed to sunlight, the elastomer pressure plate is likely to become brittle, causing the seal around the shoulder to fail. When this is no longer air-tight, the pneumatic actuation system becomes incapable of operation. Deterioration of the thin diaphragm which bears on the fuze mechanism will have a similar effect, rendering the mine incapable of functioning as designed.

G: Full Material Analysis Report

Identification of Components Harvested from Degraded Emplaced Landmines – Phase I Project Report

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1.0. Project overview

This report encompasses our second year's research into the composition of aging landmines, and how their materials interact with their environments resulting in the failure of the mine to operate as intended. Typically, aging has been thought to be an inactivation process alone, and while that is indeed the ultimate result of the aging processes, in the short term the mines may become more sensitive to triggering as individual components break down and fail to operate as intended.

In this phase, our team had the opportunity to be present as the mines were harvested from active minefields undergoing clearance operations. This provided a rare opportunity to collect soil samples, geological reference data, and materials samples from individual mines. These included Russian PMN, PMN-2, and PMD-6 landmines, as well as Chinese manufactured Type 72 mines from the northwest region of Cambodia. A second set of samples from Jordan were obtained later into this research period, and included American models M14, M15, M19 and M35.

A goal of our research in this phase of the project has been the development of field-portable, inexpensive tests to identify materials in these components. It is our aim that these tests may be used in the future by non-specialists (e.g., field operators) such that our current research may be readily built upon for additional mine types and environmental conditions.

Through our previous work, and the detailed observations and input of mine clearance specialists (e.g., Colin King of CK Associates, the staff of the Golden West Humanitarian

Foundation's Explosive Harvesting operation in Kampong Chhang, Cambodia, participants in the Senior Mine Action Managers Course at JMU), we have come to understand that the breakdown timeline of a landmine is not a linear process; rather, it is best described as a sequence of serial breakdowns based on the chemical interactions of each material with surrounding components.

Figure 1 shows a hypothetical breakdown timeline for an imaginary landmine. In reading this figure, it is important to remember that once multiple breaches have occurred in the exterior casing, this may lead to accelerated breakdown of the mine's interior workings. Also note that for a period (shown in the first grey line) the mine has become more sensitive to triggering due to a weakened pressure plate spring. The pathways highlighted in **Figure 1** are a small representation of possible breakdown processes; a true timeline for a given mine would differ based not only on its material composition for each important component, but also on its environment (e.g., hot, dry sandy soil, vs. cold, wet soil with seawater exposure).

As a result, our research focuses on the identification of the materials used in deployed-and-recovered mines. A parallel project at James Madison University (JMU) housed in the Geology Department has focused on the task of identifying and quantifying the environmental characteristics associated with each landmine. At the intersection of these two projects, a wealth of literature should be unlocked that allow extrapolation of other materials used in mine construction, and will allow new mine types and environments to be treated in a similar fashion.

2.0. Summaries by mine type

In order to predict whether a mine component may function as intended, the condition of the part must be considered in the context of its function. In this section, we provide a short overview of how the mine functions, followed by our determination of the components' compositions. A detailed analysis of the internal metallic components may be found in the scoping study report, or in the companion report prepared by Elizabeth Johnson.

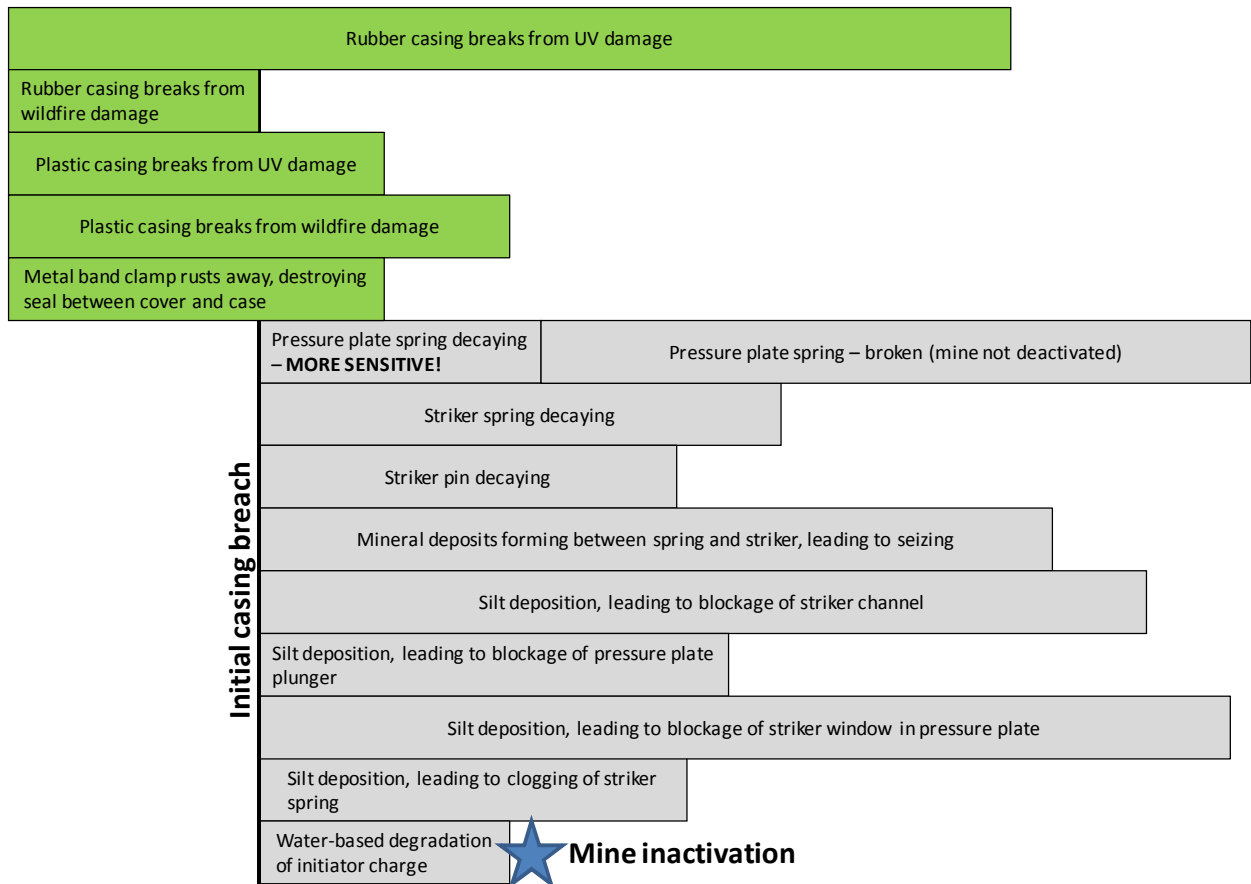


Figure 1. Hypothetical breakdown timeline for a landmine. Failures in the mine’s exterior casing are shown in green, and interior failures in grey.

2.1. PMN

The PMN has a Bakelite exterior, with a rigid rubber housing that covers the pressure plate to the top. This cover is held in place by a metal band (when new—this is commonly rusted away in emplaced mines). A Bakelite piston is spring-loaded from the bottom against the pressure plate, and is pressed downward when triggered. In its resting position, this piston blocks a spring-loaded metallic striker, holding it in its armed state. As such, a weakened piston spring will increase the sensitivity of the PMN. When the pressure plate is pushed downward, the striker aligns with an opening in the piston, allowing it to spring forward. The metal striker has a sharp firing pin along the front edge, which strikes an initiator/detonator, which in turn triggers the main explosive. If the spring around the firing pin weakens over time, it may not strike the detonator with enough force to fire the mine; if the spring gains a thick deposition layer (e.g., rust, mineral deposits) it may stick to the striker, slowing or preventing its motion and preventing detonation. If the tip of the striker degrades, it may no longer be sharp enough to trigger the initiation explosive.

2.1.1. Component identifications

The rubber cover was determined to be made from a styrene butadiene rubber, with SiO_2 as an additive. This combination is known to be durable, and is found in a variety of applications, including truck tires. These rubber components are typically found without significant damage or decomposition. Likewise, the Bakelite housing is largely unaffected by environmental processes. However, the metal band connecting the two components was heavily rusted in all observed cases. This has implications for detection (the band no longer serves as a loop antenna for metal detectors) and allows water access to the interior.

While the exterior held up well to environmental breakdown, it usually did not remain watertight throughout the emplacement time of the mine. However, in most observed mines, the function of the mine was not compromised. In the field, two PMN mines were partially reassembled without the main charge to ascertain whether the mine could still function as intended. In this test, the rubber cover and pressure plate were omitted, and a weight (guided by a large PVC tube) was dropped directly onto the trigger piston. In both tests, the mine detonated; the force from the initiator/detonator alone was sufficient to shatter the mine casing, destroy the surrounding sandbags, and shatter the bottom few inches of the PVC tube. This demonstrates that at least some of the detonators will operate as intended, and that so long as the components in the triggering sequence remained in good condition (channels not blocked by sediment, spring intact, striker free to move, striker tip sharp enough), the mine will function.

Generally, the striker assemblies examined in the Scoping Study and Phase II were able to function as intended. That said, mine failures amongst PMN mines

are most commonly attributable to metal component failures. One striker/spring assembly examined in phase I had been immobilized by mineral deposits fusing the spring and striker. Samples examined in both phases I and II had spring coils that had collapsed/broken, probably due to some sort of metal occlusion in the tin coating over the steel core.



Figure 2. Internal PMN components. The spring pieces to the far right are the striker spring, and the spring to the center holds the cylinder up.

2.2. PMN-2

To prevent easy disarming via overpressure (e.g., surface charge detonation), the PMN-2 was designed with a complex arming and firing mechanism. This increased complexity results in multiple failure points (many of which were simultaneously observed in our harvested samples). The PMN-2 has a rigid plastic housing, with a rubber cover over the cross-shaped pressure plate (mostly missing in **Figure 3**).



Figure 3. PMN-2, as recovered from the field (after rinsing).

The pressure plate presses down on a spring-loaded stepped window (similar to that of the PMN). The PMN-2 adds an additional mechanism that holds the detonator out of line with a spring; if this spring degrades, or if this channel is blocked, the detonator will not move into the proper position, and it will not simultaneously encounter the striker.

2.2.1. Component identifications

The exterior plastic casing of the PMN-2 has been identified as a poly(phenylene) oxide (PPO). The top rubber covers obtained from the field were significantly deteriorated; as a result, complete materials identification remains elusive. The rubber has been determined to be a chlorine-containing rubber, and by digesting the organic material with nitric acid, we found that ~50% of the mass is SiO_2 . IR spectra further identified the SiO_2 form to be from a quartz additive. The rubber experienced significant degradation (visually this appears to be a result of fire damage), leaving the pressure plate in contact with the soil.



Figure 4. PMN-2 with the top and rubber covering removed, showing root infiltration under the pressure plate.

As is apparent in **Figure 3** and **Figure 4**, failure of this rubber cover allowed root infiltration. This also provided ready access to the interior for water and sediment deposition. Inside, numerous metal

components had failed (e.g., the striker had expanded/mushroomed and seized in place in the stepped window, the spring attached to the detonator had failed, the striker spring had begun to collapse—all in the same mine). In the PMN-2, the failure of the rubbers probably has strongly contributed to the sequential breakdown process this mine experienced.

2.3. PMD-6

The PMD-6 is a 'box'-type mine, made up of: i.) an exterior wooden box (rarely found intact); ii.) a block of explosive, with a protective covering (wax paper? also rarely found intact); iii.) a detonator/striker assembly. The detonator assembly consists of a metal cylindrical housing, which contains a spring-loaded metal striker. The striker is held in the 'armed' position by a metal firing pin, which in the operation of the mine, is either pulled free by a tripwire or by the movement of the wooden hinged pressure plate. This striker assembly is placed directly into the main charge.

2.3.1. Component identifications

In this study, only the explosive and detonator were found intact in the field. The explosive was tested for viability by igniting a portion. The TNT charge appeared to remain viable.

However, all other parts of the triggering system appeared to be non-functional. The firing pin had rusted into place in the fuze, requiring considerable pulling force to remove (**Figure 5**). In order to access the interior components of these fuses, the housing was cut in half. The interior metal components were rusted, but overall, most seemed to remain operational (e.g., springs rusted but remained stiff). Infiltration of roots, deposition in striker channel, and dislodgement of the fuse from the TNT block are examples of the systemic causes of PMD-6 mine failure. Only one rubber component was recovered (a rubber cap that sits near the firing pin); this rubber was quite brittle. Unfortunately, this sample was too limited/too degraded for identification. All other components are discussed in the metals report (*Annex H*).



Figure 5. The fuze from a PMD-6, held in place by a bench vice.

2.4. Type 72

The Type 72 mine has the simplest mechanism of all the mines discussed here. The main body of the casing is plastic, and the mine has a rubber cover over the pressure plate. The rubber cover was typically missing in the field. The cover is held in place by a plastic ring. When pressed down, the pressure plate causes a Bellville spring (a dome-shaped

spring, rising toward the pressure plate before it is triggered) to invert. In the center of this Bellville spring, pointing downward is a firing pin. Under strain, this spring ‘pops’ downward and the pin strikes the detonator.

2.4.1. Component identifications

The simplicity of this mine’s design minimizes the possible points of failure. Only two components were commonly found in a degraded state; the rubber cover, and the firing pin. The firing pins examined in the field ranged in condition from ‘nearly pristine’ to ‘rusted away’, with many pins found in the continuum between these two states. Field tests showed the detonator to usually remain viable, a few to be inactive, and some to be capable of igniting but possibly lacking the power to initiate the booster. It is worthy of note that some degraded firing pins were still effective at initiating the detonator despite their visible state of degradation.

The cover was found to be EPDM rubber with an SiO₂ filler (subtype indeterminate). These covers were most commonly missing. Interestingly, the few rubber samples we have seen nearly all showed signs of fire damage on the mine. It cannot be determined if the rubber survived *despite* or *because of* the fire damage (perhaps a vulcanization effect?) but this question might be worth further consideration. (Might a wildfire *increase* the survivability of this mine type, if not too frequent, and not too damaging?) This question may also be moot; even the mines without rubber covers had a high likelihood of remaining viable, and the design of this mine typically keeps groundwater sediment out of the striker-detonator path, and we never observed a thick enough soil layer in a mine to prevent operation of the pressure plate.

The exterior casing of the mine was found to be a polyurethane plastic, and even with obvious signs of wildfire damage, the case was consistently intact. The O-ring that seals the top plastic ring to the main case was found to be a polyurethane rubber. The Belleville spring consists of a layered polymer/fiber disk. We did not observe any failure mode for this spring in the field.

3.0. Experimental methods

A detailed explanation of the methods used may be found in the references cited, or in the laboratory notebook for this project. This section serves to introduce a non-specialist reader to the methods used, and to give the data the appropriate context.

In practice, our most fruitful identification scheme followed this approach. The samples were analyzed via attenuated total reflectance infrared spectroscopy (ATR-IR); this non-destructive method was done first, ensuring sample size would not be an issue. Due to the complexity of the ATR-IR data, however, we used these spectra primarily to confirm our subsequent tests. ATR-IR spectra are frequently used to identify plastics and rubbers in

industry, but identifications via this method alone were unlikely to correctly identify these samples due to aging, environmental degradation, leeching and deposition processes, etc. We then used chemical tests (described in Section 0) for the identification of the plastics and rubbers. We completed the identification by digesting away the organic components of the sample with nitric acid, allowing measurement of the inorganic additives (e.g., SiO₂) alone.

3.1. Properties analysis of rubbers and polymers

In addition to the methods used in our scoping study work, we have added new (and field-portable) tests in Phase I. In particular, the museum conservation literature has been fruitful in identifying useful tests that can be successfully performed by non-chemists.^{3,4} As in the Scoping Study, we used an identification scheme centered around the Liebermann-Storch-Morawski (LSM) and Burchfield tests. These tests were augmented by those found in the aforementioned conservation literature, and two books published by Rapra Technology Ltd.

Finally, a portion of the samples was weighed, then digested in nitric or sulfuric acid. The tubes were heated in a water bath, and additional aliquots of acid were added until the digestion of the organic matter (i.e., the polymers) was complete. The samples were then centrifuged, washed to remove the acids, centrifuged again, then the solid was recovered and dried. From this the percent mass of inorganic components was determined.

3.2. Fourier Transform Infrared Spectroscopy (FTIR)

The acquisition of IR spectra followed the methods used in the Phase I Scoping Study report. Generally, we used ATR-FTIR rather than the salt-pellet methods included in our previous work.

4.0. Less fruitful methods

This section briefly describes the ‘dead-ends’ we pursued, and serves to document ideas that could be interesting, if not immediately useful.

4.1. NMR and in-tube digestion

Nuclear magnetic resonance is routinely used to identify small molecules, and with more advanced approaches, can be used to determine the structure of large, complex molecules. However, it requires the use of specialized solvents. The plastics and rubbers were not soluble in any of the tested deuterated solvents. In a second approach, we used a Soxhlet extraction setup, in the hopes that we could leech out enough uncrosslinked monomers (or small polymers) to perform an assay. After multiple days of extraction, the

solvent had changed from clear to colored. This solution was measured on the JMU Department of Chemistry 600 MHz NMR overnight in H- and C-NMR modes. No sample ever yielded sufficient signal-to-noise quality to allow any analysis. Our third approach was to attempt digestion of the polymer in an NMR tube, during sampling, acquiring in C-NMR mode. Our hope was that though the transient concentration of polymer fragments would be low at any time, that given sufficient sampling times we might recover sufficient S/N to for useful analysis. Ultimately, this direction was abandoned.

4.2. Solubility

Various sources in the polymer-analysis literature have suggested solubility in various solvents as an identifying parameter (DMSO, THF, ethyl ether, p-xylene, o-xylene, benzene, toluene, acetone, chloroform, etc.) The rubbers in this study proved to be inert to these solvents on the time scale used (days).

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H: Full Metal Analysis Report

SCIENTIFIC SUMMARY: CHARACTERIZATION OF METAL LANDMINE PARTS AND CORROSION

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GOALS

There were three goals of this study:

1. **Visual characterization of surface degradation** of metal mine parts, and in particular metal firing pins;
2. **Visual and quantitative characterization of metal firing pin degradation in cross-section**; and
3. **Compositional characterization of metal mine parts and corrosion materials.**

SAMPLES

Landmines were collected in Cambodia and Jordan (see methods from that section). This study focused on the metal firing pins from Type 72 mines from Cambodia and M14 and M19 mines from Jordan. Thirteen firing pins from Belleville springs were collected from active landmines (*Table 1*) and firing pins from four other pristine mines were also obtained and included in this study. The similarity in size and structure of the firing pins from Cambodia and Jordan allowed us to complete a detailed study of degradation of the firing pins. Pins and spring mechanisms from other mine types were also photographed and in some cases chemically analyzed, but a detailed comparison between locations or mine types was not possible.

Table 1. Sample number and mine type of recovered metal firing pins from Belleville spring triggers.

Cambodia		Jordan	
Sample #	Mine Type	Sample #	Mine Type
C1	Type 72	J1	M14
C2	Type 72	J4	M19
C3	Type 72	J7	M14
C4	Type 72	J8	M14
C5	Type 72	J12	M14
C10	Type 72	J13	M14
		J20	M14

METHODS

Parts from each landmine were photographed together with a scale bar, and were then organized in labeled boxes for archiving.

1. Visual characterization of surface degradation

A Leica binocular microscope with a digital camera attachment was used to capture images at 3x-63x magnification of metal mine parts. A scale was recorded on each image. These images were catalogued in a database and provide a record of surface features before samples were disassembled and in some cases sectioned for compositional and corrosion analyses.

2. Visual and quantitative characterization of metal firing pin degradation in cross-section

Firing pins were removed from the Belleville spring mechanism and mounted on a jig. A cross-section of each pin was exposed by using a Buehler diamond wafering saw to cut across the firing pin 1mm above the base of the pin. The surface of each cross-section was lightly polished using a custom polishing jig and table and diamond polishing paper with a 3 micrometer grit size. The exposed sections were all photographed at the same magnification, including a scale bar, using the Leica binocular microscope with digital camera attachment.

Images of firing pin cross-sections were loaded into the free software Google Sketchup (<http://sketchup.google.com/>). Using pristine pins as a guideline, the original cross-sectional area of the firing pins 1mm above the base was calculated. The cross-sectional area of remaining metal was then determined for each pin by fitting a polygon to the photograph of that pin, keeping all images at the same scale during processing.

Other parts including metal springs were sectioned and photographed but corrosion was not quantified.

3. Compositional characterization of metal mine parts and corrosion materials

The firing pins, springs, and powdered samples of corrosion materials were mounted on adhesive carbon tape and analyzed on the Zeiss scanning electron microscope (SEM) at James Madison University. Data were obtained at 25 kV and 100nA. Back-scattered electron (BSE) images were collected for pin cross-sections and springs. Qualitative chemical analyses were obtained using energy-dispersive spectroscopy (EDS) on individual spots on springs, corrosion materials, and the centers and rims of firing pin cross-sections. Detailed compositional imaging was performed on a pin cross-section, a washer at the base of one of the firing pins, and the surface of a spring mechanism.

RESULTS

1. Visual characterization of surface degradation

Firing pins from pristine mines not deployed in the field are metallic and have a regular conical shape (*Figure 1*). Firing pins from landmines collected in the field show ranges of deposition of corrosion products and changes in morphology. *Figure 1* shows a series of M14 firing pins in order from pristine condition to the most

degraded pin, sample J12, which has completely lost all of the metal from the firing pin. These photos show yellowish to reddish powder on the surface of somewhat- to moderately-degraded pins, and reddish to black massive material in those which have been the most heavily degraded. The colors and fine-grained, yet massive, growth habit of this corrosion material suggest that the corrosion product consists of one or more Fe oxides, such as the mineral hematite (Fe_2O_3).

The morphology of the pin also changes as degradation progresses. The end of the firing pin becomes rounded. In some cases the pin experiences lateral mass loss, so that the width of the pin is reduced and possibly the strength of the pin is compromised. More commonly, the most heavily corroded samples lose metal from the point of the pin, making the pin shorter. Simultaneously, growth of corrosion material occurs near the base of the pin. Extremely corroded sample J12 contains a mass of oxide material which replaces and extends laterally from the base of the pin, with the conical shape of the original pin completely lost. Field observations indicate J12 was filled with water, which would explain the oxidation of the metal and formation of iron oxide (rust).

2. Visual and quantitative characterization of metal firing pin degradation in cross-section

The percentage loss of the original circular cross-section of the metal firing pins is reported in **Table 2**. Measurement error is estimated at about 5%. Almost all of the pins show <20% loss of the original circular cross-sectional area of the metal. Thus, barring infiltration by water (as in J12) or other environmental conditions that would rapidly oxidize the metal pins, most of the original mass of the pins is preserved when landmines are deployed in the field.

Table 2. Percent loss of metal firing pin in cross-section.

Cambodia	
Sample #	% loss of metal pin
C1	0
C2	3
C3	13
C4	10
C5	2
C10	18
Jordan	
Sample #	% loss of metal pin
J1	18
J4	30
J7	15
J8	8
J12	100
J13	0
J20	2

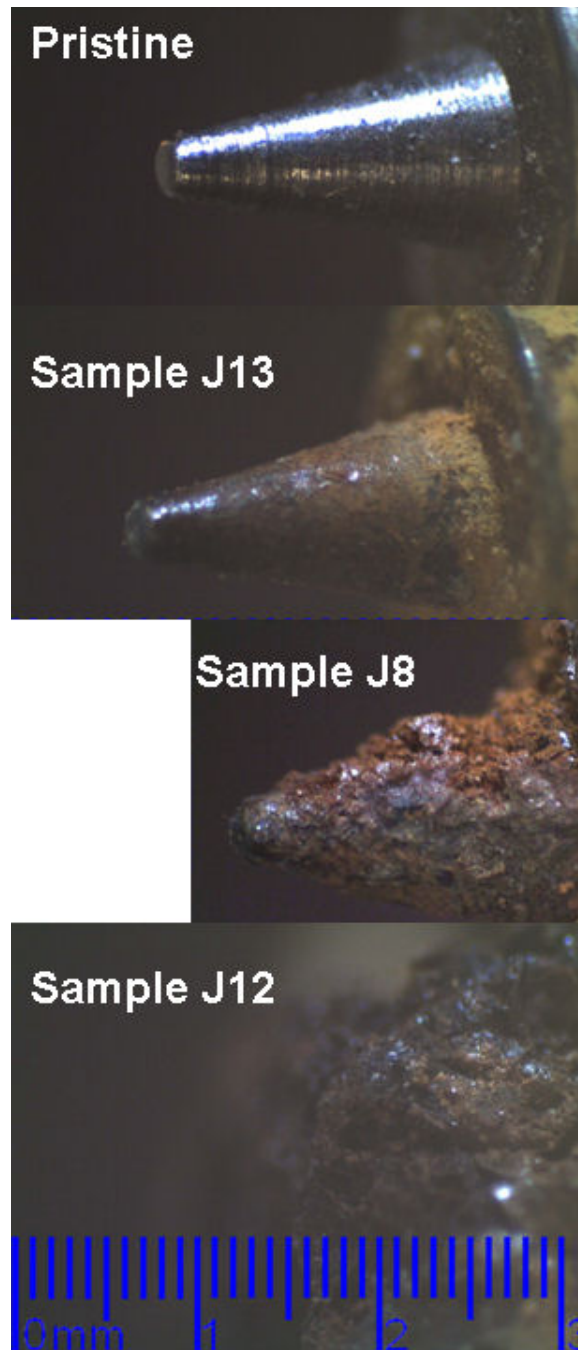
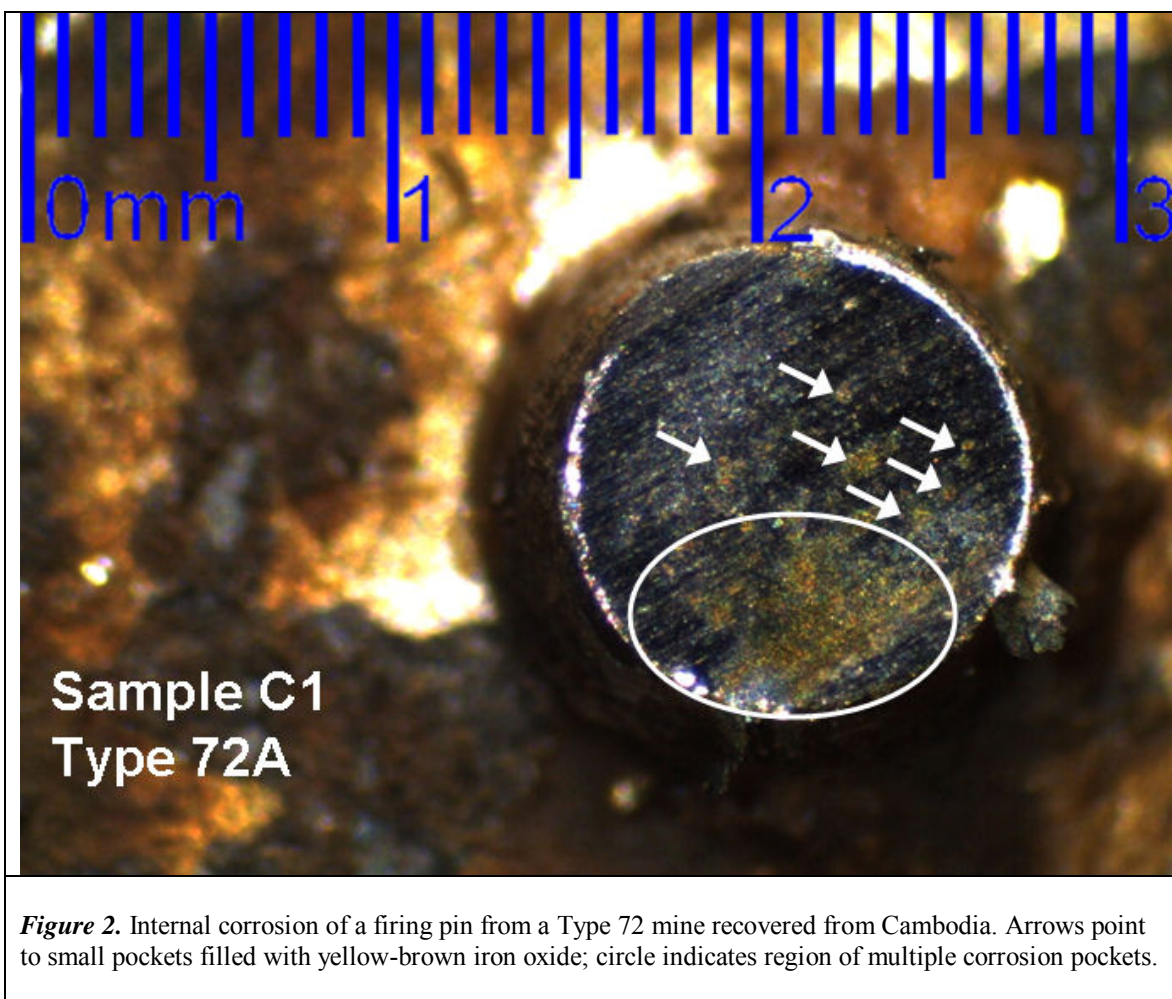


Figure 1. Variation in degradation of firing pin mechanisms in M14 mines from Jordan.

All firing pins from all three types of landmines (Type 72, M14 and M19) show at least a surface coating of corrosion material. However, only the Type 72 landmines recovered from Cambodia contain visibly corroded areas within the pins as revealed in the cross-sectional slices (**Figure 2**). This may be due to compositional differences between firing pins from Chinese-made Type 72 mines versus American-made M14 and M19 mines.



3. Compositional characterization of metal mine parts and corrosion materials

Table 3 is a summary of materials and elements present in the cores and rims of firing pins based on qualitative chemical analyses from EDS as well as texture, color, and reflectivity observations.

The Type 72 mines from Cambodia contain Fe metal pins coated with either an Sn or an Sn-Sb alloy. Other trace elements present in the pins include Hg, which may be a residue from the explosive, Mo, S, Si, Cl, and K. For sample C3, we were able to remove and analyze a circular casing that wrapped around the base of the firing pin and the Belleville spring in the immediate area of the pin. The bottom and top surfaces of this casing were analysed. The casing is a Cu-Ni alloy with a Sb coating on the top surface exposed to the explosive.

Table 3. Summary of materials and elements in firing pins identified from EDS.

Sample #	Mine Type	Center of pin	Outer edge of pin	Casing at base of pin
C1	Type 72	Fe metal with minor Mn	Fe oxide with trace Si, Cl, K, and Mo	
C3	Type 72	Fe metal with minor Sn, Sb and trace O, S, Cl	Sn and Sb metal alloy and oxide, Hg (explosive residue?), with minor Mo and trace Fe and Cl	Cu-Ni metal alloy with Sb coating, minor Fe oxide, S, Cl, K, Br
C4	Type 72	Fe metal with minor O, Si	Sn metal; layer of Fe oxide just within the Sn layer	
C5	Type 72	Fe metal with minor O, Hg, Sb, Sn, trace Al, Si, Cl, K	Fe oxide, with trace S, Cl, K	

Jordan				
Sample #	Mine Type	Center of pin	Outer edge of pin	
J7	M14	Fe metal and Fe oxide, with minor Cd, Si, Mn	Fe oxide with minor Cd metal, trace Al, Si, S	
J12	M14	Fe oxide with minor Cd (pin is completely corroded)		
J13	M14	Fe metal and Fe oxide with minor Cd, Mn	Cd metal with Fe oxide and trace Al, Si, S	
J20	M14	Fe metal with minor Mn	Cd metal with minor Fe metal	

Figure 3 is a back-scattered electron image of a cross-section of the Type 72 pin from sample C4. EDS analyses locations and compositions are shown. The pin is coated with Sn metal; the firing pin itself is made of Fe metal with trace amounts of Mn and Si. A layer of Fe oxide has formed between the Sn coating and the Fe metal pin. Tin is often used as an anti-corrosion layer; it is likely that water and/or other corroding agents breached the Sn layer and oxidized the Fe metal firing pin producing Fe oxide (rust).

The M14 and M19 firing pins from Jordan are made of Fe metal, possibly containing Cd, Mn, and Si. These pins are coated with a layer of Cd metal. Minor Al, Si, and S are also present in the outer edge or rim of the pins.

Although the compositions vary among landmine types, all firing pins are made of Fe metal and are coated with a layer of corrosion-resistant metal such as Cd, Sn, or Sn and Sb.

IMPLICATIONS

1. All analyzed firing pins are made of Fe metal and are coated with a thin layer of non-corroding metal. Type 72 landmines from Cambodia have firing pins coated with Sn or a Sn-Sb alloy; M14 and M19 landmines have firing pins coated with Cd metal.
2. If groundwater or rainwater (which has perhaps also picked up chemical constituents from the explosives within the landmine or from the environment) penetrates the mine casing and breaches the protective coating on the surface of the firing pin, the Fe metal pin will corrode to produce Fe oxide (rust).

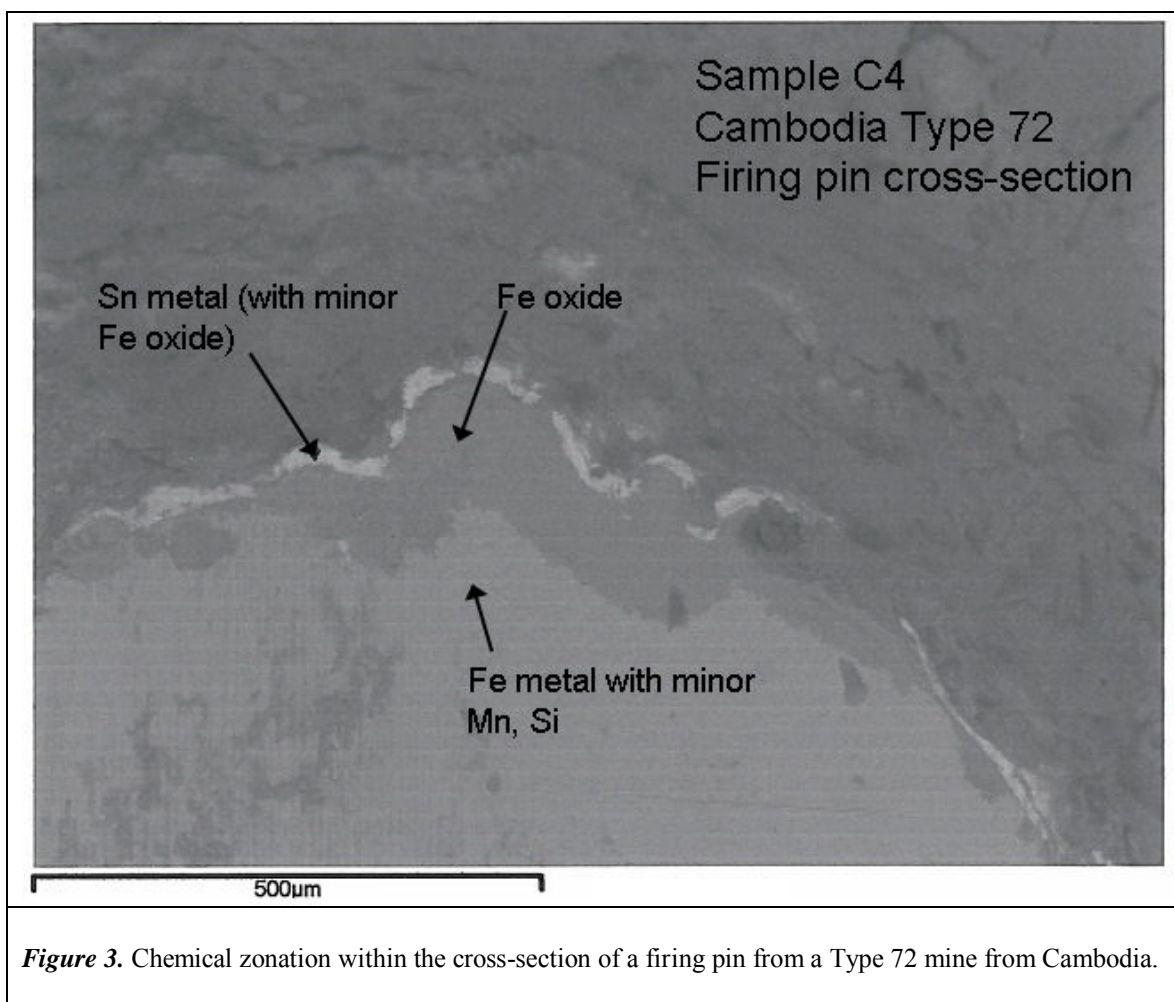


Figure 3. Chemical zonation within the cross-section of a firing pin from a Type 72 mine from Cambodia.

3. Upon corrosion, the shape of the firing pin changes from a longer, conical shape to a blunter, shorter shape. The most severely corroded firing pin has no Fe metal remaining and is a mass of Fe oxide material (rust), with no point remaining.
4. Most pins showed minimal loss of Fe metal in cross-section. This suggests that the protective metal coating on the firing pins is often effective at protecting the pin from degradation. Once the coating is breached, however, a water-rich environment will rapidly degrade the pin, which may potentially render the landmine unable to function as intended due to the blunter shape and reduced strength of the pin.
5. The firing pin is unlikely to be the first component to fail in the Type 72, M14, or M19 landmines since it is housed internally, but it may be a good indicator that a mine is unlikely to function as intended, and may be able to initiate any longer at all. Almost all firing pins from deployed landmines with show corrosion on the surface. The shape of the firing pin is one indicator of how far corrosion had progressed; quickly slicing or cutting the pin open will reveal how much original metal remains. If 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 likely that most landmines in the area

are degrading and unlikely to 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.

I: Full Soil Analysis Report

Landmine Aging Project Final Report: Characterization of Soils Associated with Cambodia and Jordan Landmines

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SUMMARY

No single soil property such as pH or percent soil organic matter best explained patterns of landmine functionality, particularly where we were able to quantify soil properties associated with functional *and* non-functional landmines of the same type (e.g., PMN, M14, M35).³⁴

Nevertheless, this study shows that several soil properties appear promising as indices of environmental settings likely to be associated with rapid aging (degradation) of landmines, including very ‘high-level’ or ‘master’ soil variables such as pH (how acidic a soil is), texture (how sandy or clayey a soil is), and soil carbon. Furthermore, our results suggest several more ‘esoteric’ variables could also be useful in ‘fingerprinting’ landmine aging (e.g., soil carbon-to-nitrogen ratios (C:N) or levels of tin, antimony, or other trace elements used in the manufacturing of landmine components).

GOALS

There were two goals of this study:

- **Characterization of soil properties** associated with landmine parts, with a particular focus on properties likely to influence corrosion or degradation;
- **Development of quantitative relationships between soil properties and landmine characteristics.**

INTRODUCTION

There seems to be a geophysical ‘gold rush’ underway in the handling of unexploded ordnance. Recent advances in geophysical technologies, for example, have been

³⁴ The terms ‘functional’ and ‘non-functional’ in application to landmine samples for this research do not mean the mines have been *confirmed* to work or not work. Rather, the terms represent samples that have been identified by technical experts during field review as *likely* to function as intended, or *unlikely* to function as intended. For mines *unlikely* to function as intended, this could mean a mine does not function at all, or else functions in a way different than intended—possibly more dangerous or possibly less dangerous. However, for the sake of this analysis we are focusing on mines unlikely to function as intended that are for practical purposes non-functional if activated by pressure.

celebrated for their abilities to detect unexploded ordnance.^{35,36} The promise of these technologies is that they will “distinguish between UXO and harmless objects,” an important accomplishment since “field experience indicates... in excess of 90% of objects excavated during a munitions response are found to be nonhazardous.”

While these geophysical approaches are certainly impressive in their abilities to distinguish composition (ferrous from non-ferrous metals, presumably based on k-wave returns), shapes, and depths of buried objects, the positive identification of UXO (or mines) based on ‘macro’ physical and chemical characteristics *does not necessarily mean that functional UXO can be identified, or most importantly, that functional UXO can be distinguished from non-functional UXO.*

Such a quantum leap in UXO management requires models of explosive-remnants-of-war aging that incorporate both out-of-the-box vulnerability to degradation as well as environmental setting characteristics most likely to influence degradation, both in concert with geophysical advances. This coupling of landmine and soils characterization and geophysical techniques is not novel, but it does represent a more nuanced perspective than is evident in even quite recent research. For example, Preetz et al. (2007) suggest landmine detection with metal detectors is hampered in tropical lateritic soils.³⁷ But *how do aging landmines additionally or multiplicatively complicate detection*, in addition to complexities associated with soil properties?

A Scoping Study in 2008 examined the effects of aging on landmines in Cambodia and found that many types of landmines appear to cease functioning as intended due to processes associated with aging.³⁸ This report summarizes research activity associated with the first phase of follow-up study, aimed at quantifying soil properties in the vicinity of landmines, and with an eye which was aimed at understanding the factors most likely to contribute to landmine aging. A keener understanding of these factors should assist in reprioritization of clearance efforts and direction for future R&D, leading to innovative solutions and efficiencies for mine action and clearance. Specifically, it is believed that findings may assist the development of more effective countermeasures, allowing some suspected hazardous areas to be more quickly released for use, and clearance resources to be diverted to more appropriate areas, in addition to catalyzing new R&D efforts.

Aging of landmines involves the chemical weathering and physical breakdown of the numerous components that comprise a typical landmine. Because corrosion of metallic components is fundamentally driven by reduction-oxidation reactions, we targeted soil

³⁵ Billings, S. and L. Beran. 2010. Robust statistics and regularization for feature extraction and UXO discrimination. Poster #81, SERDP Project Munitions Response-1629. SERDP/ESTCP Symposium, Washington, DC, 30 November 2010.

³⁶ Prouty, M. 2010. Performance of the MetalMapper EMI system at former Camp Butner. Poster #94, ESTCP Project Munitions Response-200603. SERDP/ESTCP Symposium, Washington, DC, 30 November 2010.

³⁷ Preetz, H., S. Altfelderb, and J. Igela. 2007. Tropical soils and landmine detection—An approach for a classification system. *Soils Science Society of America Journal* 72(1): 151-159.

³⁸ http://maic.jmu.edu/aging/aging_intro.html

properties and landmine characteristics that may help ascertain the relative importance of these types of reactions to aging processes.

CONCEPTUAL MODEL

We have approached the issue of landmine aging from a quantitative pedological perspective. Pedology is the study of soils, and at its marrow, addresses the question “Why do soils have the properties they do?” Traditionally, pedology has been largely descriptive, and dominated by efforts to map current soil properties. There are two fundamental tacks that can be taken: (i) a correlative approach, that summarizes ‘soil-forming *factors*’ thought to most strongly influence soil properties, and (ii) a *process*-based approach, where the underlying processes are defined and quantified.

The most popular *factor* approach suggests that soil properties (S) can be regarded as a function of a number of interacting factors.^{39,40} A *process*-based approach, by contrast, seeks to quantify processes that transform soils.^{41,42}

Raymond Siever (1974)⁴³ first conceptualized these dynamics in an article “The steady state of the Earth’s crust”; William Schlesinger (1997)⁴⁴ reformulated this central concept as:

³⁹ Jenny, H. 1941. *Factors of soil formation; a system of quantitative pedology*. New York: McGraw-Hill.

⁴⁰ ...such as climate (cl), biota (o), relief (r), parent material (p), time (t; but really duration of soil-forming processes), and human activities (h):

$$S(tn)=f(cl,o,r,p,t,h,...)$$

The ellipses hints at either interactions between these primary factors (e.g., cl x r) or additional factors.

⁴¹ E.g., Schaetzl, R. J., and S. Anderson. 2005. *Soils: genesis and geomorphology*. Cambridge: Cambridge University Press.

⁴² For example, precipitation in excess of evapotranspiration will generally increase soil moisture, and because soils host billions of living (‘respiring’ or carbon dioxide [CO₂]-producing) bacteria, moist soils act as blankets of acidity as water absorbs CO₂ to produce carbonic acid (H₂CO₃), which, as with any acid, can split apart (dissociate) in solution to form H⁺:



pH is a measurement of acidity, and is defined as the negative logarithm of the concentration of H⁺ (-log H⁺); because of the negative sign, pH and acidity are inversely related. As pH increases, the concentration of H⁺ (acidity) decreases, and as pH decreases, acidity increases. Because of the logarithmic relationship, every 1 unit change in pH translates to a 10-fold increase or decrease in acidity. Thus, the average Cambodia pH (6.1) is ~32 times more acidic than the average Jordan pH (7.6).

Acidity, in turn, attacks primary minerals such as a granite or limestone bedrock, converting these ‘parent materials’ into secondary minerals. One consequence of this weathering is that the most mobile ingredients in parent material are unleashed from their mineralogical dungeon, whereupon they follow gravitational and hydrological pathways to their ultimate ‘base level’: the ocean. This is why the oceans are salty: acidity generated by micro- (and macro-) organisms and roots has attacked minerals that contain cations (salts) such as calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), and potassium (K⁺). In essence, hordes of H⁺ (acidity) bump salts into soil solution, from whence they travel to the lowest part of the planet, the ocean.

⁴³ Siever, R. 1974, The steady state of the Earth's crust, atmosphere and oceans: *Scientific American*, v.230, p.72-79.

⁴⁴ Schlesinger, W. H. 1997. *Biogeochemistry: an analysis of global change*. San Diego, Calif: Academic Press.

igneous rock + acid volatiles → sedimentary rocks + salty oceans

The research team reformulated this as the ‘salty ocean equation’—a fundamental organizing principle for understanding chemical weathering and, by analogy, landmine aging, in soils.

parent material + H_2CO_3 → clays + salty oceans


A pedological approach to landmine aging, therefore, is the substitution of landmines for parent material. This approach seeks a process-based, rather than empirical, predictive model for the trajectory of landmine functionality.

METHODS


Physical sample collection and transfer to JMU Soils Lab. Personnel affiliated with the Center for International Stabilization and Recovery sampled 16 locations for both soils and associated landmine parts in the ‘K-5’ belt of Cambodia in November 2009; an additional 10 locations were sampled for soils and associated landmine parts in northern Jordan in May 2010. Numerous georeferenced photographs were obtained. In total, 33 soil samples were collected for transport to the James Madison University (JMU) Soils Laboratory under USDA Permit #P330-09-00212, reproduced in *Figure 1*. In this report, we focus on those 26 samples for which soils and landmine parts were obtained simultaneously.⁴⁵

Cambodia samples generally were sourced from two locations: 13.56°N, 102.41°E and 13.59°N, 102.57°E. Jordan samples were also generally sourced from 2 locations: 32.54°N, 36.08°E and 32.51°N, 36.20°E. Using the georeference data collected by the field researchers, soil/mine sample locations were then overlaid onto available maps identifying soil types, as seen in *Figures 2* and *3*.

⁴⁵ While 33 soil samples were collected for research, only 26 intact soil-landmine sample pairs were transported to James Madison University because some mines were deemed too high risk to move or study further or were unable to be safely defuzed. Specifically, no landmine components were characterized for Cambodia soil samples C11 and C16, or for Jordan soil samples J2, J3, J5, J6, or J14, so we do not present the corresponding soils data in this report.



Animal and
Plant Health
Inspection Service



Plant
Protection &
Quarantine

United States Department of Agriculture
Animal and Plant Health Inspection Service
4700 River Road
Riverdale, MD 20737

Permit to Receive Soil
Regulated by 7 CFR 330

This permit was generated electronically via the ePermits system.

PERMITTEE NAME: Dr. Anthony Spencer Hartshorn COMPANY: James Madison University RECEIVING ADDRESS: 800 S. High Street MSC 6903 Harrisonburg, VA 22807 MAILING ADDRESS: 800 S. High Street MSC 6903 Harrisonburg, VA 22807 PHONE: (480) 406-1277 FAX: (540) 568-8058	PERMIT NUMBER: P330-09-00212 APPLICATION NUMBER: P525-090518-001 DATE ISSUED: 10/19/2009 DATE REVISED: EXPIRES: 10/19/2012	
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PORTS OF ARRIVAL/PLANT INSPECTION STATIONS: Various Ports of Entry Staffed by CBP-Agriculture Inspection

HAND CARRY: No

Under the conditions specified, this permit authorizes the following:
Quantity of Soil per Shipment and Treatment
 Over 3 lbs

Figure 1. USDA Permit for soil transport to James Madison University.

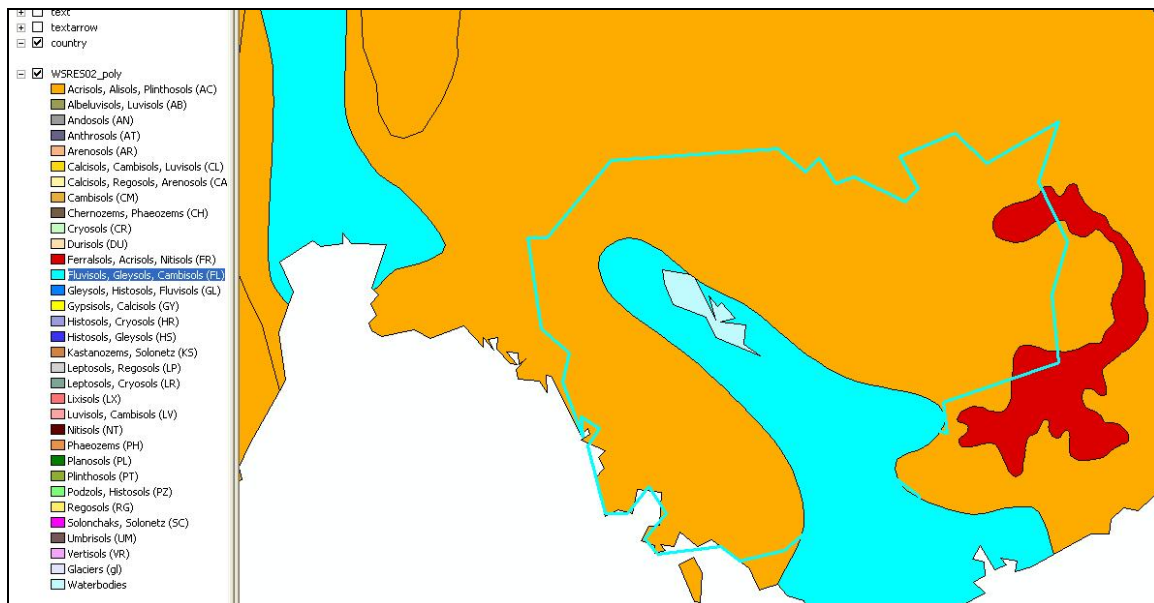


Figure 2. World Reference Base soil map units associated with Cambodia (outlined in blue). Soils and landmines were collected from the northwestern corner of the country, in soils mapped as “Acrisols, Alisols, and Plinthosols (AC).”

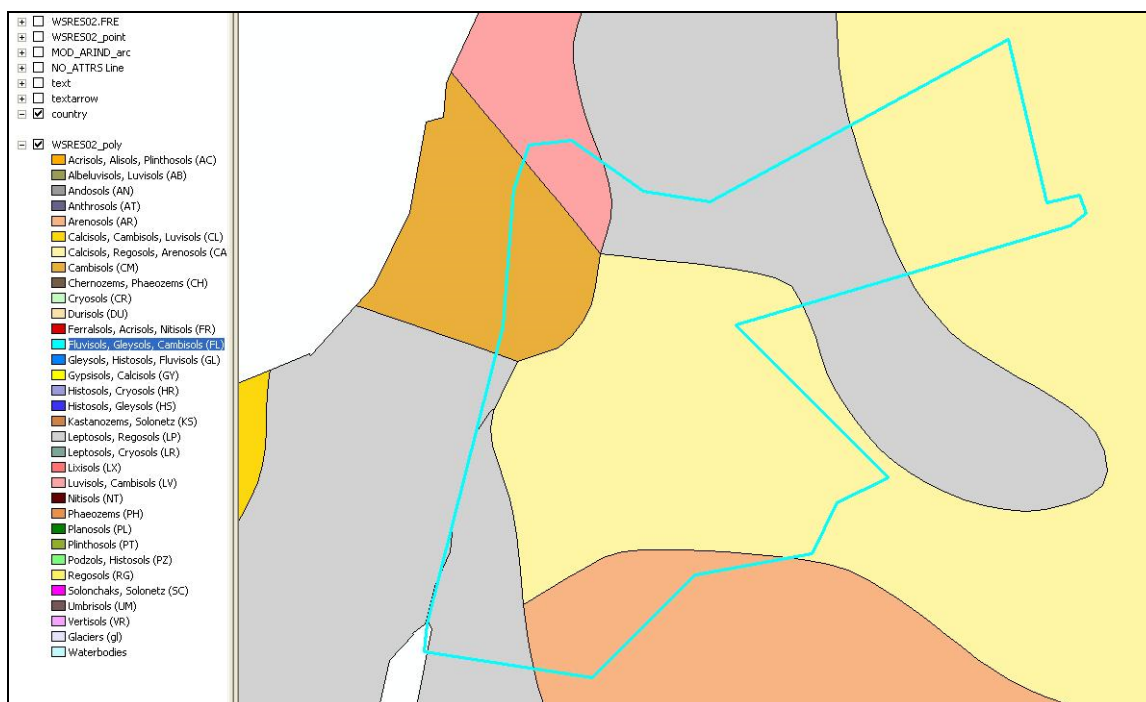


Figure 3. World Reference Base soil map units associated with Jordan (outlined in blue). Soils and landmines were collected from the northern part of the country, in soils mapped as “Leptosols and Regosols (LP).”

Research methods undertaken at JMU Soils Lab. Upon receipt in the laboratory, all samples were air-dried and sieved at 2 mm. All further mentions of soil refer to <2-mm material. In one instance, a Jordan rock sample was discovered during sieving. This sample was analyzed to assess the chemical differences between the soil associated with the landmine and the soil’s ‘parent material.’

The research team characterized 9 soil properties as part of this study (**Table 1**). Coefficients of variation (CV), used to quantify the variability of a procedure by dividing the standard deviation of duplicate results by the average result, were calculated as well.

Soil pH was measured by adding 10 ml of distilled water to 10 g of air-dry soil, stirring, allowing to sit for 30 minutes, and then inserting a calibrated, handheld pH electrode into the supernatant. For pH, CVs ranged from 0 to 2%.

Electrical conductivity was measured using a calibrated, handheld electrode in the same supernatant as pH; CVs ranged from 3-34%.

Soil texture was measured using a hydrometer on a mixture of 40 g of soil and a dispersant/deflocculant to break soil particles apart (sodium hexametaphosphate/sodium carbonate). Soils were pretreated with ~30% hydrogen peroxide. CVs for sand, silt, and clay were 13, 6 and 21%, respectively.

Table 1. Summary of soil properties measured.

Property	Rationale	Units
pH	index of soil acidity	
electrical conductivity (EC)	index of soil salinity	deciSiemens per cm (dS/cm)
texture	index of water-holding capacity	<i>percent sand</i> [2 mm>particles>0.05 mm], <i>percent silt</i> [0.05 mm>particles> 0.002 mm], and <i>percent clay</i> [0.002 mm>particles] by hydrometer
color	index of organic matter and clay content	Munsell color chart: hue value/chroma
soil organic matter (SOM)	essential precursor for generation of biological acidity	percent; assumed equal to loss of weight upon combustion
total soil carbon & nitrogen	the ratio of C to N can index microbial activity	percent
base saturation	index of soil acidity	centimoles of positive charge per kilogram of oven-dry soil (cmol+/kg-l)
‘major’ elements	composition of soil	typically percent
‘trace’ elements ⁴⁶	composition of soil	typically parts per million by weight

We also used the soil textures to derive a number of additional soil properties, including:

- Bulk density (an index of organic matter content, g cm⁻³)
- Saturated hydraulic conductivity (a measure of how quickly water can move through soil; m sec⁻¹)
- Saturation (a measure of soil pore space; cm³ cm⁻³)
- Field capacity (a measure of soil-retained water after gravitational drainage; cm³ cm⁻³)
- ‘Wilting point’ (a measure of soil-retained water at 1.5 megapascals [MPa] of pressure; cm³ cm⁻³)
- Plant available water (measured as the difference between field-capacity and ‘wilting point’ moisture; expressed in centimeters)

Soil colors are typically expressed as *hue*, *value* and *chroma*. *Value* and *chroma* CVs were 0-47%. These relatively high CVs occurred because the difference between paint chips with chroma 1 and 2 is the standard deviation (0.71) divided by the average (1.5).

Hues correspond to a specific wavelength region of the visible part of the electromagnetic spectrum and can be calculated using a color book such as the Munsell color book (Figure 4).^{47,48} CVs for hues were 0% because all hues were 10YR (‘yellow-red’).

⁴⁶ Typically, ~80% of soils derived from igneous rocks is comprised of SiO₂, Al₂O₃, and Fe₂O₃, but we expected trace elements might enable us to learn more about the ‘aging process’.



Figure 4. Example of a page from a Munsell color book used to quantify soil color.

Soil organic matter was assumed to equal the percent loss-on-ignition (LOI), which was calculated by measuring the weight loss in a departmental muffle furnace (6 hrs at 400°C) after oven-drying the soil samples to constant weight (typically 24 hrs at 105°C); 6 minutes in a microwave suffices for typical air-dried soils to obtain ‘constant weight.’

The research team used the equation:

$$\% \text{LOI} = 100 * (\text{post-microwave weight [wt]} - \text{post-furnace wt}) / (\text{post-microwave wt})$$

CVs for LOI ranged from 0-33%, averaging 10%.

Total carbon and total nitrogen were obtained by shipping samples to the Ecosystems Analysis Laboratory at the University of Nebraska Lincoln (<http://www.biosci.unl.edu>). CVs for total carbon ranged from 5-11%, while CVs for total nitrogen ranged from 0-9%.

⁴⁷ Hues correspond to a specific wavelength region of the visible part of the electromagnetic spectrum and are indicated in the upper right hand corner of the right hand page (e.g., 10YR, for ‘yellow-red’); value is read on the vertical axis and is an indication of the saturation of color, higher values being lighter and lower values being darker (e.g., 4/6); and chroma is read along the horizontal axis and is an indication of the purity of color, with lower chroma associated with grayer colors (e.g., 4/6). A very readable introduction to color in general is Ball 2001: 24-49.

⁴⁸ Ball, P. 2001. Bright Earth: Art and the invention of color. Chapter 2: Plucking the rainbow: The physics and chemistry of color. New York: Farrar, Straus, and Giroux. ISBN 0374116792.

Base saturation measurement CVs typically are <20%. These cations were extracted from representative 1-g soil samples using 20 ml of 1 M ammonium acetate (NH₄O(C₂H₃O)); samples were shaken vigorously for 1 hr, and then allowed to sit for ~23 hrs before extraction on a vacuum manifold.

Major and trace elements were analyzed by x-ray fluorescence (XRF; light gray) or inductively coupled plasma-mass spectrometry (ICP-MS; dark gray) by ALS Chemex, Reno, NV.

RESULTS

Landmine analyses. Detailed characterizations of landmines were performed by Dr. Johnson, Dr. Davies, and Mr. King. We highlight the potential importance of some of these analytical results in the discussion section. Although 33 landmine and/or soil samples were collected in total and analyzed for this project, representing 10 different landmines types, this report focuses on the complete, matched 26 landmine/soil pairs for which landmines and soils were available and brought back to JMU (Table 2).

Table 2. Summary of numbers (total numbers/numbers used for soils analysis report) and vulnerability index values (in parentheses).

Mine Type	Cambodia	Jordan
Type 72	2/2 (21)	
Type 72	4/4 (21)	
M14		6/5 (17)
M15		2/0 (19)
M19		2/1 (8)
M35		4/3 (16)
MK5		1/1 (*)
PMD-6	3/3 (27)	
PMN	8/6 (19)	
PMN-2	1/1 (21)	
Grand Total	18/16	15/10

* No vulnerability index value was assigned.

As **Table 2** shows, no landmines complete with accompanying soil were encountered in **both** countries during this phase of research.⁴⁹ The research team concluded that having overlapping, identical landmine types would have helped in the interpretation of factors likely to influence landmine aging.

⁴⁹ In the previous Scoping Study as well in anecdotal, support research conducted in the Falkland Islands and other places, landmines were studied that overlap between the countries; however, these samples had no soil collected with them and therefore could not be included for the soils analysis research.

The greatest number of landmines were of the PMN type (8/33), which was assigned a vulnerability index (VI)⁵⁰ value of 21 (**Table 2**). Of the 10 different mine types, VI values ranged from 8 (the antitank M19, collected from Jordan) to 27 (the antipersonnel PMD-6, collected from Cambodia).

Of the 6 PMN landmine/soil pairs assessed in this study, half were deemed capable of functioning as intended, based on an evaluation of fieldnotes recorded upon collection of the landmine sample.

SOIL PROPERTIES

Cambodia soils contained more soil organic matter (7.8%, see **Figure 5**) and had a lower pH (6.1; see Figure 6) than Jordan soils (4.2% and 7.6%, respectively). These patterns were reflected in soil colors, which we summarized by dividing the Munsell chroma by the Munsell value. Average Cambodia soil chroma/value were 0.7 (darker), whereas average Jordan soil chroma/value were 1.5 (brighter).

Specific calculations combining soil property characteristics for macro analysis were also conducted. **Figure 5** shows the comparison of soil organic matter (%) between Cambodia-only, Jordan-only, and combined (C+J) soils in relation to the field estimates of whether the target landmines might be capable of functioning as intended: *Yes*, probably capable of functioning as intended; *No*, probably not capable of functioning as intended; or *Maybe*, no clear conclusion of functionality could be determined from field assessment.

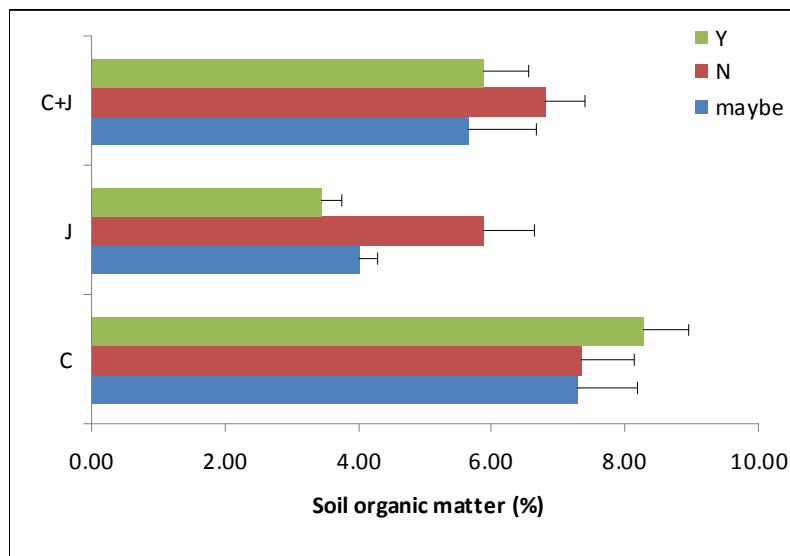


Figure 5. Comparison of soil organic matter (%) between Cambodia-only, Jordan-only, and combined (C+J) soils.

⁵⁰ For discussion on vulnerability index, see Section 6, “Moving Beyond: Vulnerability Tools, Extrapolation and Final Analysis” and Annex J, “Full Summary of Report on Models.”

Figure 6 also depicts a paired comparison for three landmine types (M14 and M35 from Jordan, PMN from Cambodia) of associated soil properties, between samples identified as likely to function and samples likely to not-function as intended. Average soil organic matter (%), pH, and EC (dS m^{-1} ; /200) ($\pm 1\text{SE}$) for were measured for:

- non-functioning (yellow dotted; $n=1$) and functioning (red; $n=9$) M14 landmines (Jordan)
- non-functioning (yellow dotted; $n=2$) and functioning (red; $n=2$) M35 landmines (Jordan)
- non-functioning (yellow dotted; $n=3$) and functioning (red; $n=5$) PMN landmines (Cambodia)

These analyses suggest an important interaction between country or climate and soil properties. The two non-functioning Jordan landmines (M14 and M35) had higher soil organic matter and slightly higher EC, whereas the non-functioning Cambodia landmine (PMN) had lower soil organic matter and EC, although in all cases, the variance within a specific landmine category was greater than the difference between functioning and non-functioning landmines. Only minor differences were noted in pH between functioning and non-functioning landmines.

For two of these three mine types, landmines that were determined to no longer function as intended were associated with more acid soils, although the largest average difference was only 0.5 pH units. For the M14 landmine, this greater acidity was associated with greater soil organic matter (6.0 vs. 3.7%) surrounding non-functioning landmines, whereas for the PMN landmine, the non-functioning landmines were found in soils with slightly lower soil organic matter (8.2 vs. 9.2%). Soils adjacent to non-functioning Jordan landmines had slightly greater EC, but those adjacent to non-functioning PMN landmines had slightly lower EC.

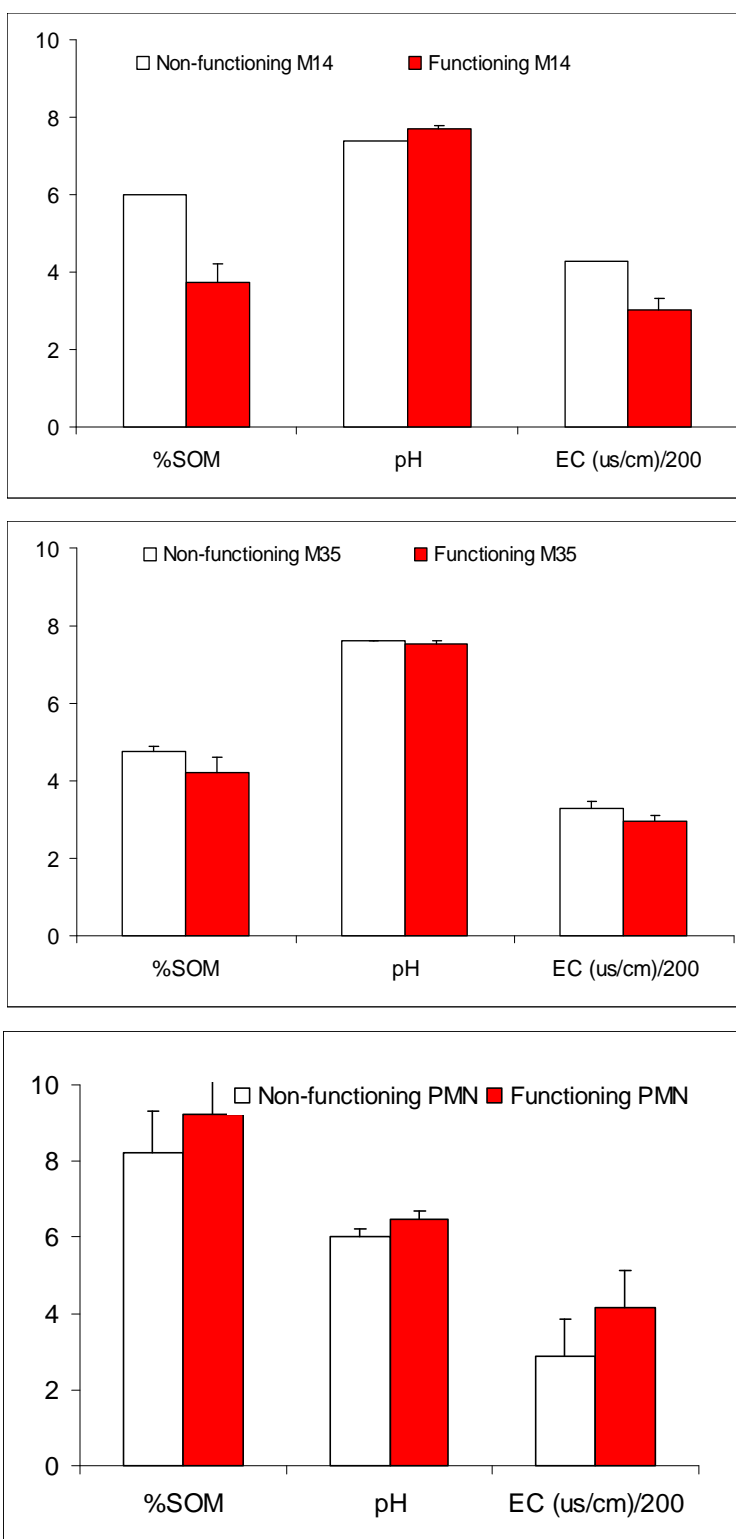
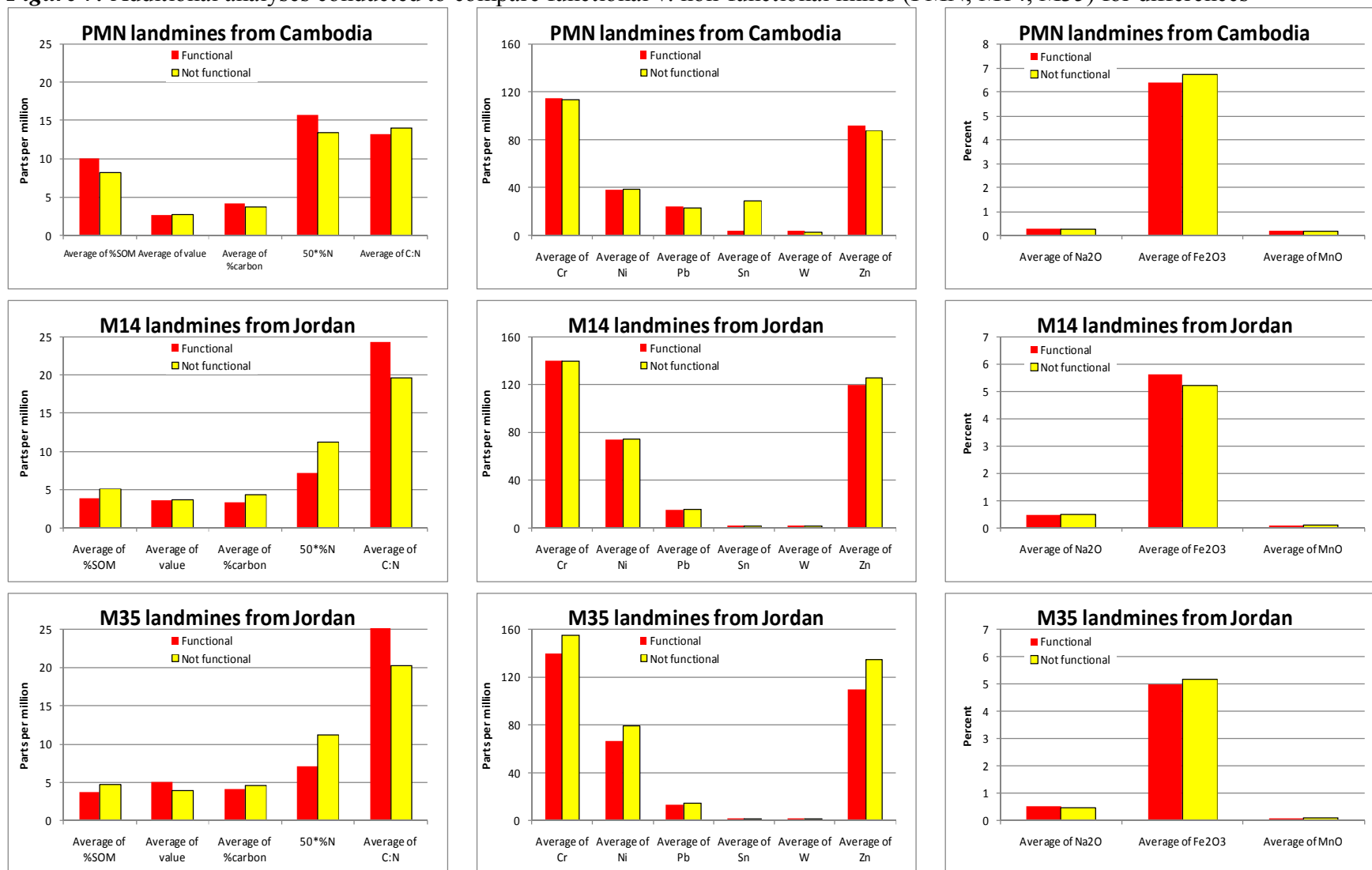


Figure 6. Three comparisons of mine type (M14, M35, PMN) measurements (soil organic matter, pH and EC) by functionality.

Additional comparisons between mines identified as potentially functional and non-functional were generated using a variety of soils analyses to look for significant differences. **Figure 7** shows some of these comparative results for PMN, M14 and M35 samples.

Figure 7. Additional analyses conducted to compare functional v. non-functional mines (PMN, M14, M35) for differences



Additionally, all six types of landmines were analyzed in larger-scale groupings by type and based on whether they generally were found to function or not function. Half of the six mine types (Type 72, M15 and M19) were deemed to have samples capable of functioning as intended during field analysis. For this subset, soil organic matter levels were higher in soils surrounding non-functioning landmines and pH levels were lower, although EC values generally overlapped for soils surrounding functioning and non-functioning landmines (**Figure 8**).

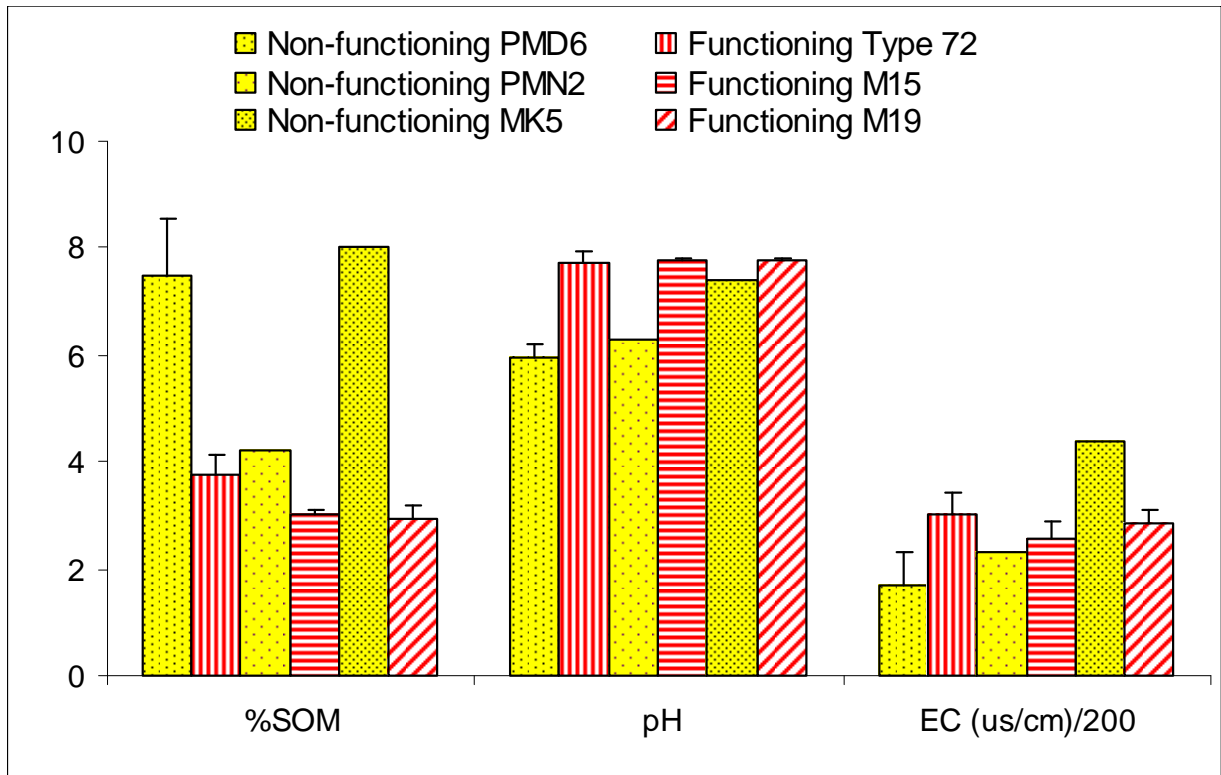


Figure 8. Comparison of soil properties for various groupings of 'functional' and 'non-functional' landmines, as determined via in-field assessments of landmine component conditions.

As **Figure 9** shows, consistent with the soil organic matter trends, Cambodia soils were finer-textured (17% sand) than Jordan soils (35% sand). Jordan soils contained twice as much silt as Cambodia soils, consistent with the climate and proximity to loess-generating areas. The greater clay content of the Cambodia soils is consistent with prolonged chemical weathering under a hot and moist climate.

These textural differences led, in turn, to nearly 4x-higher estimated hydraulic conductivities (the rapidity with which water can move through soils) for Jordan soils vs. Cambodia soils (0.66 vs. 0.17 cm sec^{-1} ; **Table 3**).

Soil ECs were similar (Cambodia: $560 \pm 60 \text{ dS cm}^{-1}$; Jordan: $630 \pm 40 \text{ dS cm}^{-1}$).

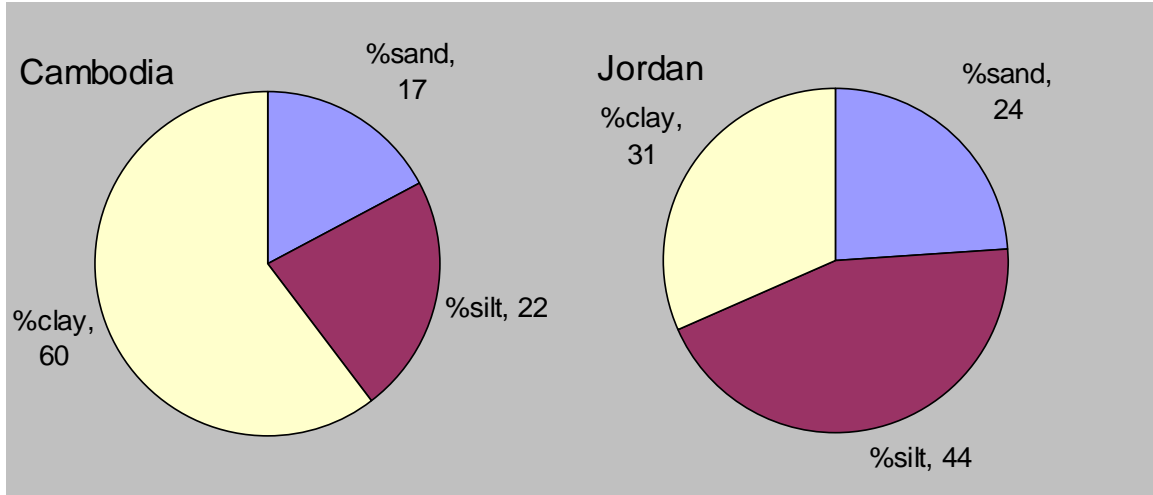


Figure 9. Comparison of average soil textures for Cambodia and Jordan soils.

Table 3. Derived soil moisture properties for soils associated with different landmines.⁵¹ M14(N) refers to a ‘non-functioning as intended’ M14 landmine, whereas M14(Y) refers to a ‘likely to function as intended’ M14 landmine; mines estimated to be capable of functioning as intended are highlighted in green.

Mine Type	Type 72	M14 (N)	M14 (Y)	M15	M19	M35 (N)	M35 (Y)	MK5	PMD-6	PMN (N)	PMN (Y)	PMN-2
Percent sand	18	25	22	23	22	25	26	21	24	14	13	28
Percent clay	58	25	31	33	33	36	31	33	54	66	63	51
Percent silt	24	50	47	44	45	39	43	46	22	20	24	21
Texture	Clay	Silt loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay loam	Clay	Clay	Clay	Clay
Bulk density	1.21	1.35	1.31	1.3	1.3	1.29	1.32	1.3	1.23	NA	NA	1.25
Saturated hydraulic conductivity	0.19	0.66	0.43	0.37	0.38	0.3	0.4	0.38	0.17	NA	NA	0.16
Saturation	0.54	0.49	0.51	0.51	0.51	0.51	0.5	0.51	0.54	NA	NA	0.53
Field capacity	0.47	0.3	0.33	0.34	0.34	0.35	0.33	0.34	0.44	NA	NA	0.42
Wilting point	0.34	0.14	0.17	0.18	0.18	0.2	0.17	0.18	0.31	NA	NA	0.29
Plant available water (cm)	0.14	0.16	0.16	0.16	0.16	0.15	0.15	0.16	0.13	NA	NA	0.13

NA: Not applicable; algorithm does not encompass such clayey textures.

In addition to these characteristics, many which can be easily quantified or estimated in the field (e.g., color, texture, pH, and EC), the research team analyzed Cambodia and Jordan soils for four exchangeable base cations (calcium [Ca²⁺], magnesium [Mg²⁺], potassium [K⁺], and sodium [Na⁺]). Additionally, the team also analyzed all soils for the total forms of these four cations, traditionally reported as percent oxides: CaO, MgO, K₂O, and Na₂O, respectively.

Together, these four cations comprised 1.5-3.3% of the total makeup of Cambodia soil samples and 11.7-20.0% of Jordan soils. The majority of the soils were comprised of 45 other ‘major’ and ‘trace’ elements. ‘Trace’ elements are typically found at extremely low concentrations; instead of percent, typical units are parts per million, or µg g⁻¹. Three elements (Ba, Cr, Sr) were analyzed twice, via the two different methods (p. 136).

As is typical for soils, the most common element was silica, or SiO₂; SiO₂ is found in quartz, which is an important component of sand. The median SiO₂ concentration was 60% in Cambodia soils, slightly greater than the median concentration of 47% for Jordan soils. The next 3 most common ‘components’ of the soils were ‘loss-on-ignition’ (LOI, obtained by ashing soils at 1000°C for 1 hr), aluminum (Al₂O₃), and iron (Fe₂O₃). For Cambodia | Jordan soils, median values of these constituents were 16.5 | 20.0, 12.1 | 10.0, and 6.1 | 5.3 %, respectively. So taken together, SiO₂+Al₂O₃+Fe₂O₃+LOI accounted for 82-94% of the soils.

⁵¹ See http://www.pedosphere.com/resources/texture/triangle_us.cfm.

Figure 10 depicts the comparison of the average sums of three ‘major’ elements (SiO_2 , Al_2O_3 , and Fe_2O_3) between Cambodia and Jordan, as well as two additional ‘major’ elements (CaO , MgO). The greater proportion of SiO_2 , Al_2O_3 , and Fe_2O_3 is consistent with the higher clay content, while the greater proportion of the two principal ‘base’ cations, Ca and Mg, is consistent with dust-influenced, arid ecosystems.

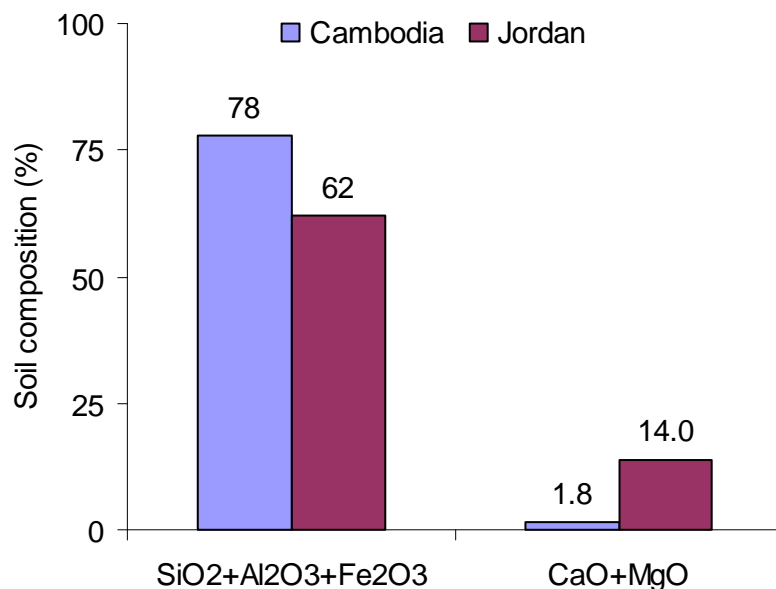


Figure 10. Comparison of the average sums of different ‘major’ elements between Cambodia and Jordan soil samples

Figure 11 shows a comparison of loss-on-ignition data from two procedures. These data would imply that LOI as quantified in the JMU Soils Lab underestimates SOM for Jordan soils relative to Cambodia soils with the same %LOI. For example, a JMU LOI value of 4% could be associated with a Cambodia ALSC LOI value of 10%, but a Jordan ALSC LOI value of 18% (see dashed vertical line).

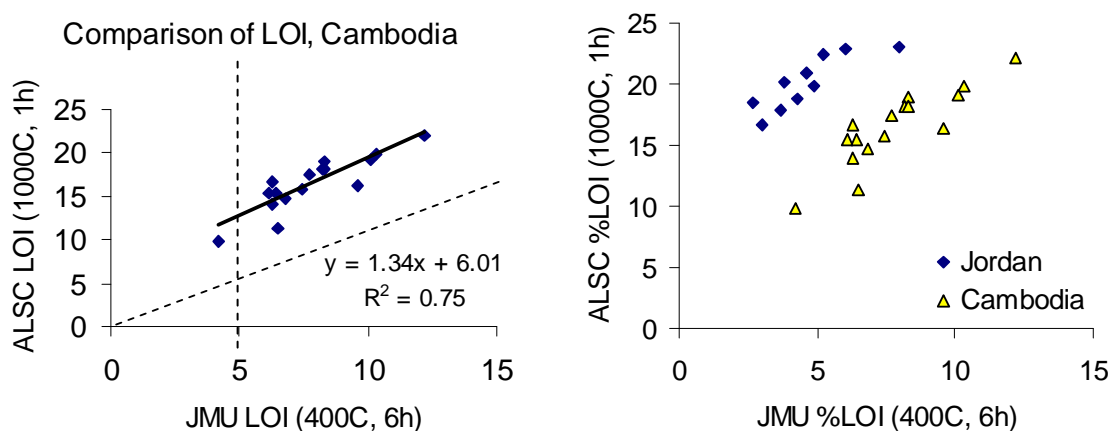


Figure 11. A comparison of loss-on-ignition data from two procedures.

Figure 12 exhibits the comparison of explanatory power of LOI to predict soil carbon. To check this whether JMU LOI underestimated soil carbon relative to ALSC LOI, we regressed JMU LOI against soil carbon and found that JMU LOI explained 77-89% of the variance in soil carbon, as determined at the University of Nebraska, a slightly greater proportion of the variance than when ALSC LOI was regressed against soil carbon (67-79%).

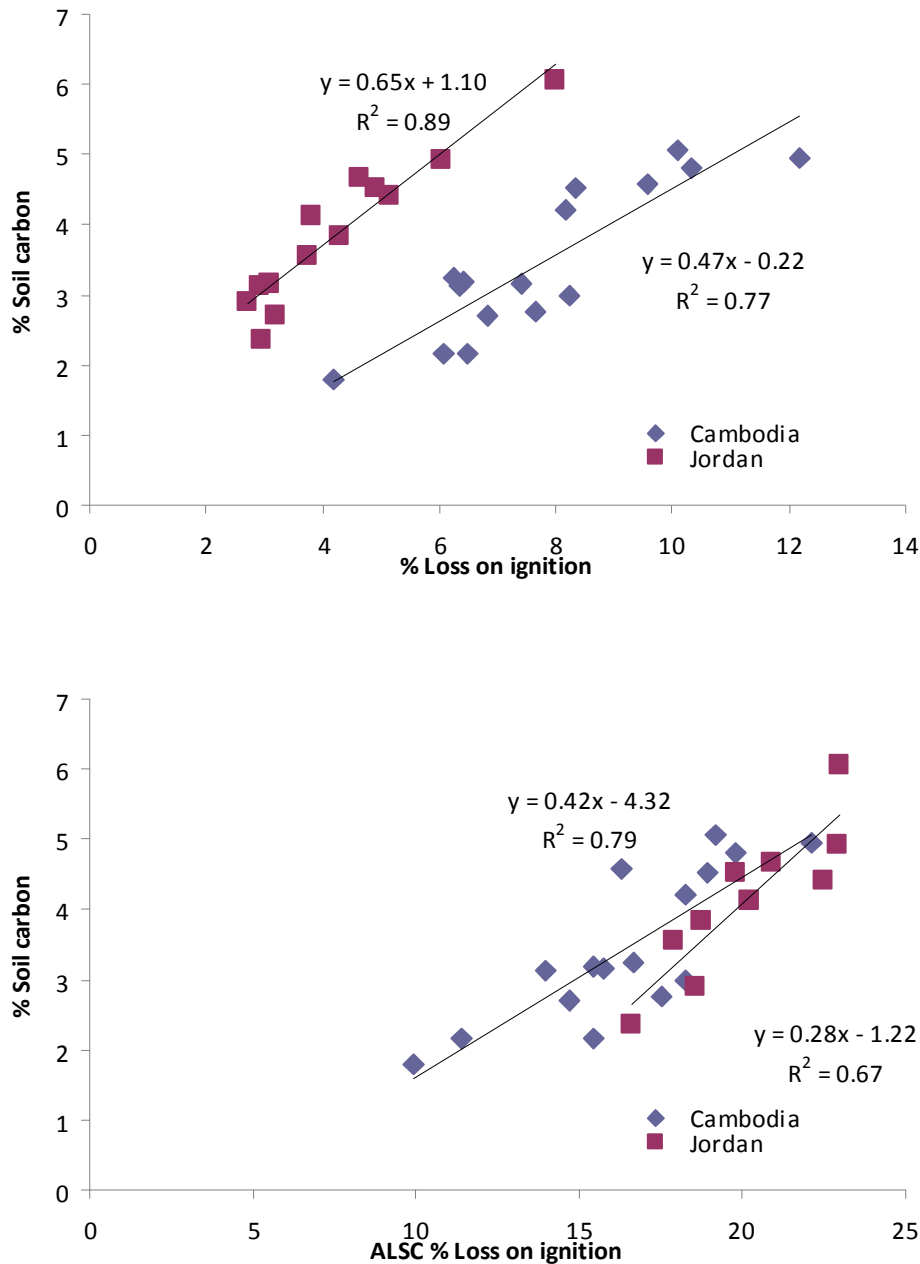


Figure 12. Comparison of LOI explanatory power to predict soil carbon.

The graph in **Figure 13** captures the somewhat unexpected result that Jordan soils contained slightly more⁵² soil carbon than Cambodia soils. Although we estimated that Cambodia soils contained more soil organic matter than Jordan soils based on our loss on ignition results, the combustion of soils at high temperatures can also release ‘waters of hydration’—or crystalline water held tightly within clays, so tightly that it is not ‘baked off’ even at temperatures greater than 100°C.

A less surprising result is that while the soil carbon values are comparable, soil nitrogen values were not. This is illustrated in the comparison of carbon-to-nitrogen ratios (C:N), which shows that the Jordan C:N were much higher than the Cambodia C:N. In fact, nitrogen in Jordan soils averaged 0.17%, about 36% less than Cambodia soils (0.27%).

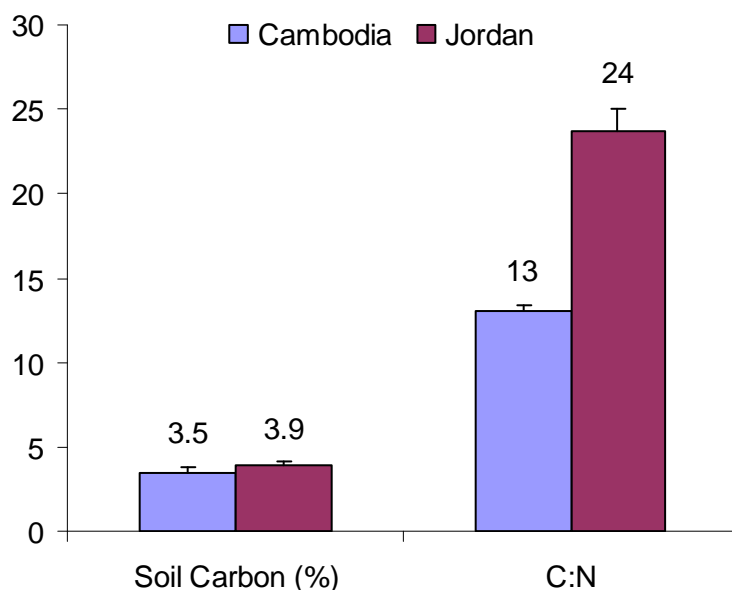


Figure 13. Soil carbon and carbon-to-nitrogen ratios of Cambodia and Jordan soils

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. As indicated in **Table 4**, both functional and non-functional PMN landmines had relatively high C:N, implying potential nitrogen limitation of soil decomposition processes. Conversely, all PMD6 landmines were deemed not functional and yet showed the greatest range in C:N.

⁵² (although most likely not *significantly* more since 1 standard error of the mean [SE] is ~0.3%)

Table 4. Test of whether lower soil C:N might be associated with more rapid landmine aging, conducted on sample mines from Cambodia and with median Cambodia and Jordan ratios

Soil sample	C:N	Associated mine	Field functionality assessment
C6	14.7	PMD6	'Not likely functional'
C7	9.0	PMD6	'Not likely functional'
C8	11.3	PMD6	'Not likely functional'
C9	14.1	PMN	'Likely functional'
C12	15.0	PMN	'Not likely functional'
C13	14.0	PMN	'Not likely functional'
C14	13.2	PMN	'Likely functional'
C15	12.5	PMN	'Likely functional'
C17	13.2	PMN	'Not likely functional'
Median Cambodia	13.2	--	--
Median Jordan	22.8	--	--

At the other end of the concentration spectrum, several elements were present at levels below the instrument detection limit (DL): silver (Ag) was only detected in 1 of 17 Cambodia soils and 1 of 11 Jordan soils (DL: $1 \mu\text{g g}^{-1}$); molybdenum was not detected in any Cambodia soils (DL: $2 \mu\text{g g}^{-1}$), but was found in all Jordan soils (range $2\text{-}3 \mu\text{g g}^{-1}$); thallium was detected in 9 of 17 Cambodia samples (DL: $0.6 \mu\text{g g}^{-1}$; range $1.7\text{-}3.2 \mu\text{g g}^{-1}$), but none of the Jordan samples.

Of potentially greater interest for the purposes of quantifying landmine aging are landmine constituents such as tin (Sn), particularly since Sn values showed some of the greatest ranges across all 50 constituents. For example, as **Table 5** illustrates, three Cambodia samples (C7, C12, and C17) contained $>20 \mu\text{g Sn g}^{-1}$, although 7 other Cambodia samples contained only $2 \mu\text{g Sn g}^{-1}$.

Table 5. Test of whether soil tin concentrations might provide field indication of landmine aging for Cambodia samples, with median Cambodia and Jordan concentrations

Soil sample	Tin concentration ($\mu\text{g Sn g}^{-1}$)	Associated mine	Field functionality assessment
C6	4	PMD6	'Not likely functional'
C7	23	PMD6	'Not likely functional'
C8	7	PMD6	'Not likely functional'
C9	3	PMN	'Likely functional'
C12	34	PMN	'Not likely functional'
C13	14	PMN	'Not likely functional'
C14	5	PMN	'Likely functional'
C15	5	PMN	'Likely functional'
C17	39	PMN	'Not likely functional'
Median Cambodia	3.5	--	--
Median Jordan	2.0	--	--

Figure 14 presents the Table 5 calculations of tin concentration in Cambodia samples graphically for another way of understanding the data. In a comparison of soils collected with PMN (n=6) and PMD-6 (n=3) landmines in Cambodia, average (± 1 SE) tin concentrations in the vicinity of landmines assessed as ‘not capable of functioning as intended’ were $20 \pm 6 \mu\text{g Sn g}^{-1}$, whereas average tin concentrations next to ‘likely to function as intended’ landmines were $4 \pm 1 \mu\text{g Sn g}^{-1}$. These results suggest that corrosion of landmines could be associated with ‘leakage’ of Sn into the surrounding soil. Tin, therefore, might be useful in chemically ‘fingerprinting’ aging landmines since one consequence of the corrosion of landmines will be the release into the surrounding soil of ‘weathering products’ such as tin.

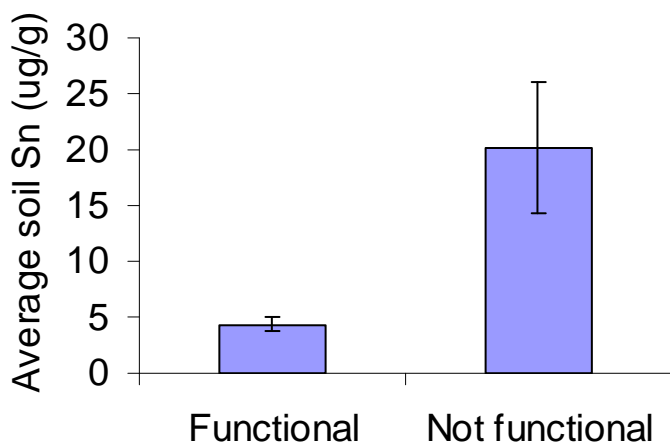


Figure 14. Graphical summary of **Table 5** soil tin concentrations in landmines identified as likely to function or not function, from samples in Cambodia

It is important to note, however, that the relatively small sample size precludes broader generalizations. First, nearly the same range of values ($4\text{--}23 \mu\text{g Sn g}^{-1}$) was observed in soils collected adjacent to two non-functional PMD6 landmines. Second, Jordan samples J7 and J8 were collected adjacent to ‘functional’ and ‘non-functional’ M14 landmines, respectively, but the soils contained identical concentrations of tin: $2 \mu\text{g Sn g}^{-1}$.

This finding illustrates well an important outcome of this research. The Jordan results fall short of being an adequate test of the tin-leakage finding because even if some tin leakage had been associated with corrosion of the M14 landmines, the sandier textures (only $\sim 31\%$ clay) of the Jordan soils (versus $\sim 60\%$ clay for Cambodia soils) could have resulted in greater leaching of any ‘leaked’ tin. Future work should target material properties associated with landmines distributed across gradients of potential leaching. The most accessible of these gradients would be catenas, or hillslopes, where the same landmines can be found at crests (relatively dry) and at toeslopes (relatively wet).

Only one other element (barium [Ba]) showed as great a range as Sn (20) in Cambodia soils; ICP-MS values for Ba ranged between 122 and 2270 $\mu\text{g g}^{-1}$, whereas XRF values ranged

between 0.01 and 0.24%. Similarly pronounced ranges were not encountered in Jordan soils: phosphorus as P_2O_5 ranged between 0.17 and 0.57%, and lead (Pb) ranged from 14 to 53 $\mu\text{g g}^{-1}$.

One rock sample from Jordan was analyzed to gain some insights into the extent of chemical weathering observed in Jordan soils, using standard mass balance approaches.^{53,54}

$$\text{tauSi} = ((\text{Soil Si} * \text{rock Zr}) / (\text{soil Zr} * \text{rock Si})) - 1 * 100$$

If we assume zirconium (Zr) is an immobile element in these soils, the ratio of median Si in soil to the Si in the rock, divided by the ratio of median Zr in soil to the Zr in the rock yields the not-too-surprising finding that the Jordan soils have lost 98% of the Si present in the parent material rock. This loss is extremely difficult to reconcile with the relatively sandy textures (and therefore, quartz- and SiO_2 -rich content of the soils).

Furthermore, applying the same calculations to Ca and Na produces losses of 15 and 72 percent, respectively. It is difficult to imagine how losses of these cations, which are important components of ocean water—and a reason the oceans are salty, could be *smaller* than losses of Si, and in the case of Ca, nearly 7 times smaller. These data point to an increasingly well-recognized phenomenon: arid soils are more frequently born of aeolian parent material (dust) than the underlying rock.

In contrast with the Cambodia soils, where we observed some large differences in elemental chemistry between samples, most Jordan soils were quite comparable. There were, however, pronounced differences between the single rock sample that was analyzed and the median Jordan soils. Nineteen elements showed order-of-magnitude or greater differences between the median soil concentration and the single rock sample: Ce, Co, Eu, Ga, Hf, Nb, Nd, Pr, Rb, Sm, Ta, Th, Zr, and among the ‘major’ elements, Al, Ca, Mg, K, Ti, and LOI.

IMPLICATIONS AND CHALLENGES OF CURRENT RESEARCH

This study has highlighted the soil properties associated with a number of different landmines collected from Cambodia and Jordan since 2009. Unfortunately, because no comparisons of the same landmine deployed for different intervals of time in the same soil were available, nor the same landmine deployed for identical intervals of time across different soils, our initial investigation of the soil properties most likely to predict the trajectory of ‘landmine aging’ has failed to zero in on a single ‘most promising’ soil property meriting further study.

⁵³ Brimhall, G. H., O. A. Chadwick, C. J. Lewis, W. Compston, I. S. Williams, K. J. DANTI, W. E. Dietrich, M. E. Power, D. Hendricks and J. Bratt. Deformational Mass Transport and Invasive Processes in Soil Evolution Science 255:695-702.

⁵⁴ Muir, J.W. and J. Logan, 1982. Eluvial/illuvial coefficients of major elements and the corresponding losses and gains in three soil profiles. J. Soil Science 33: 295-308.

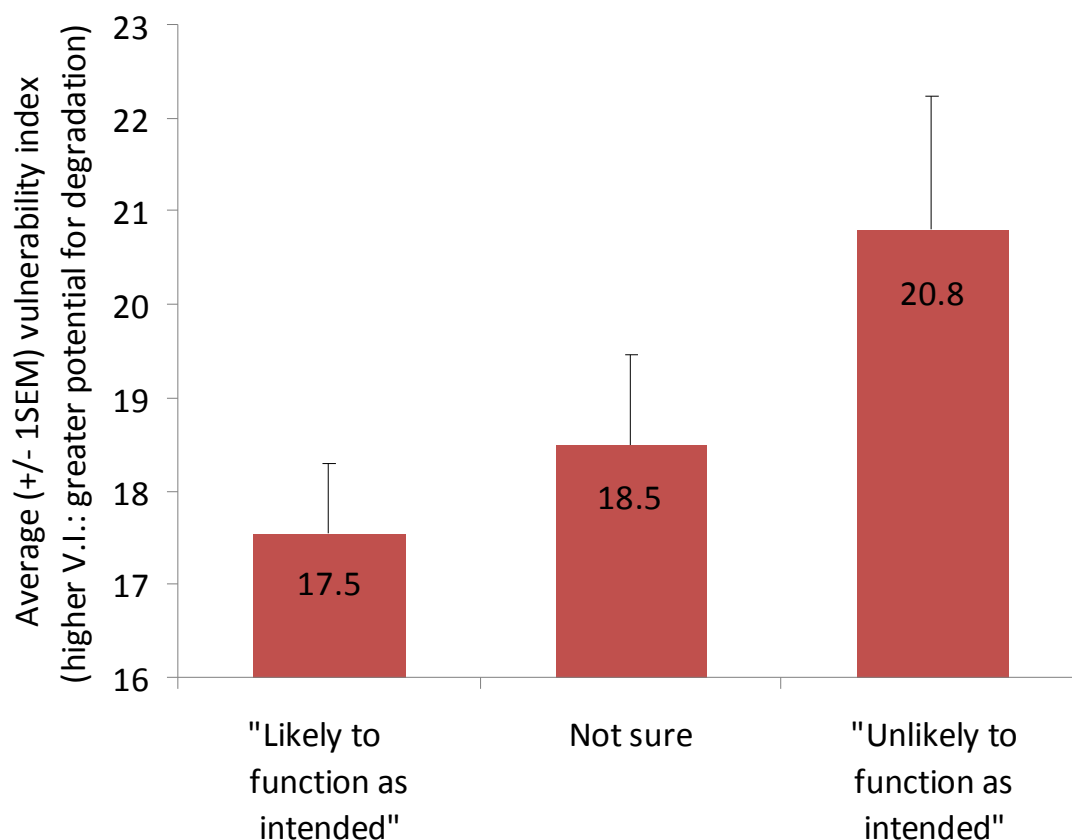


Figure 15. Average vulnerability index of all sample mine types grouped by field assessment of likely functionality.

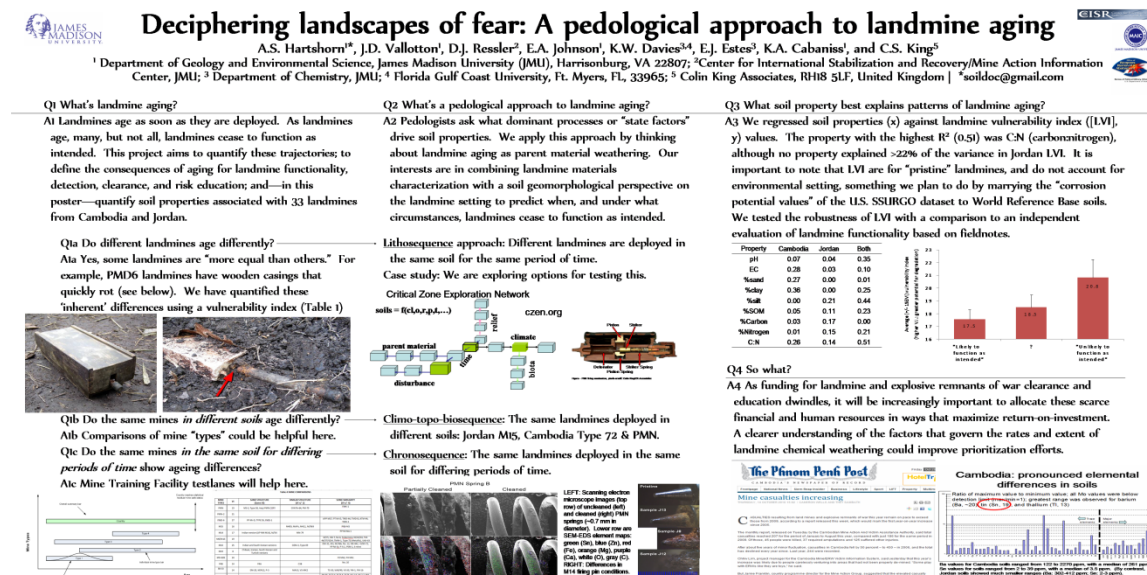
As **Figure 15** indicates, the research team's field assessments of landmine condition and likelihood of functioning as intended generally tracked the vulnerability index values developed during this phase of the Aging Study by the research team. This comparison suggests field assessments may provide a robust means of categorizing landmine aging, although much greater resolution of vulnerability x environmental interactions—as these interactions affect landmine aging and degradation—might be possible through sampling strategies that maximize a gradient approach to landmine aging.

At the Fall 2010 Geological Society of America Annual Meeting,⁵⁵ preliminary results from this project were presented in a poster comprised of 4 sections, each headlined by a question:

- Q1. What is landmine aging?
- Q2. What is a pedological approach to landmine aging?
- Q3. What soil property best explains landmine vulnerability to aging?
- Q4. So what?

⁵⁵ Hartshorn, T., "Deciphering landscapes of fear: A pedological approach to landmine aging" (GSA paper 192-14), Fall 2010 Geological Society of America Annual Meeting, Denver, Colorado, Oct 31-Nov 3, 2010.

The poster developed for the Geological Society of America Annual Meeting is reproduced in **Figure 16**. This poster highlighted primary work on elemental concentrations for Cambodia soil in order to focus on one approach to indexing the variability within Cambodia soils and between Cambodia and Jordan soils.



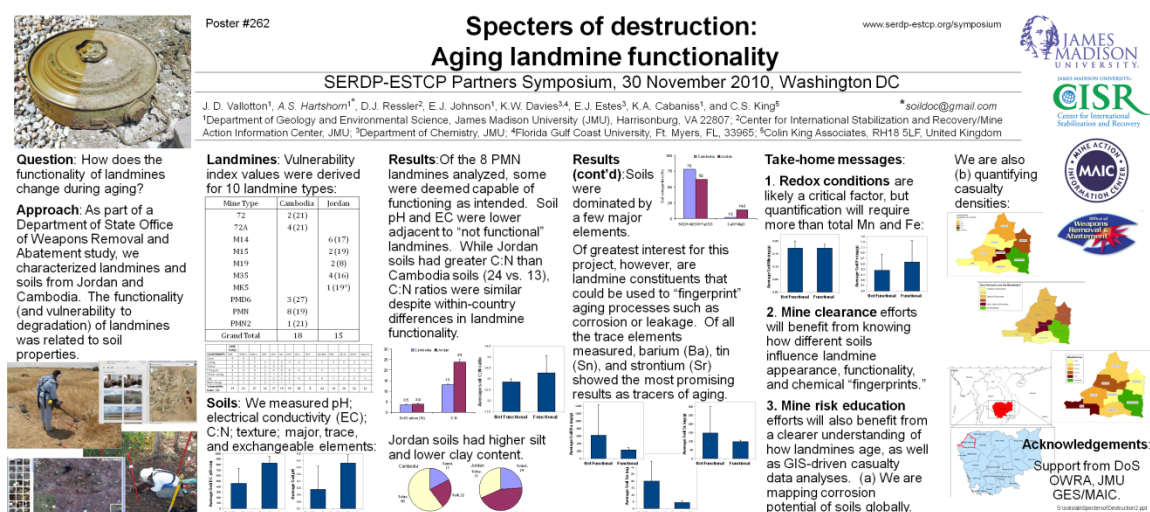
In order to better understand the question asked in poster presentation, "What soil property best explains landmine vulnerability to aging?", the research team calculated the explanatory power of different soil properties, with respect to vulnerability index values (**Table 6**). The outcome of this analysis indicates that the soil property best explaining landmine vulnerability depends on whether the landmines are considered by region (Cambodia, Jordan) or together. For all landmines together, the carbon-to-nitrogen ratio (C:N) explained 51 percent of the variance in vulnerability index values (highlighted in green), while silt explained 44 percent of the variance.

The Denver poster reception was generally enthusiastic. One individual from the New Mexico Institute of Technology noted that the soil properties that had been analyzed (for the poster: pH, EC, texture, soil organic matter, carbon, and nitrogen) were 'agricultural' and that what would probably drive landmine aging would be water. The research team agreed and noted that we cannot measure the moisture content of the soil over the 'lifetimes' of deployed landmines, and so we are attempting to index not only soil moisture, but acidity, with soil properties such as soil organic matter, which is comprised mostly of the elements carbon and nitrogen, as well as texture. Together, these are the two soil properties that are best used for indexing soil moisture.

Table 6. Summary of explanatory power of different soil properties with respect to vulnerability index values. Values can range from 0 to 1, where 1 would mean that all of the variance in vulnerability index values is explained by that specific soil property.

Property	Cambodia	Jordan	Both
pH	0.07	0.04	0.35
EC	0.28	0.03	0.10
%sand	0.27	0.00	0.01
%clay	0.36	0.00	0.25
%silt	0.00	0.21	0.44
%SOM	0.05	0.11	0.23
%Carbon	0.03	0.17	0.00
%Nitrogen	0.01	0.15	0.21
C:N	0.26	0.14	0.51

The research team also presented a poster at the SERDP/ESTCP Annual Symposium⁵⁶ where the research project's major and trace element work was expanded upon (see **Figure 17**).



⁵⁶ Vallotton, J and T. Hartshorn, "Specters of destruction: Aging landmine functionality" (poster #262), SERDP/ESTCP Annual Symposium, Washington, Nov 30, 2010.

Commentary from attendees of the 2010 SERDP/ETSCP Symposium highlighted two future considerations. The first is to investigate the potential for characterizing landmine components and soils associated with Israeli minefields; these could profitably be compared with Jordan samples, with potentially similar climates and soils. The second is to investigate other southeast Asian minefields, where landmine emplacement might reflect different region-specific conflicts, thus enabling ‘time-stamping’ of landmine aging trajectories, if the same landmines can be characterized (e.g., PMN). For example, conflicts in Cambodia, Laos and Vietnam have led to the creation of minefields that may hold the same landmine types, but laid at different times—all with potentially comparable climates and soils. Characterization of PMN landmines that were emplaced in similar soils during different time periods might profitably help clarify the trajectories of landmine aging.

One major outcome of initial soils analysis, which the Denver poster in particular clarified, is the recognition that the approach undertaken during this phase of Aging Study research was unusually constrained with respect to landmines and aging processes. Just as parent rock weathering extents will vary as a function of the various soil-forming factors and the processes, so too will landmines be affected by environmental aging processes.

Unfortunately, however, due to real-world field collection constraints faced during the current phase of research, this pilot and, arguably, proof-of-concept study did not afford access to identical mines with deployment dates ranging across decades (a soil chronosequence approach, where the one factor that is experimentally manipulated is duration of soil-forming factors or processes).

Rather, this study relied on 18 soil samples from Cambodia and 15 soil samples from Jordan. All mines that were characterized were specific to the country of origin, so even though soil properties differed between Cambodia and Jordan, we were unable to assess functionality of the same landmine deployed into two broadly different soil types.

The scope of current research on aging effects on landmines was limited, and ultimately the research team faced the problem of not being able to conduct research techniques that allowed a comparison of **identical mines deployed for identical durations** into:

- soils representing a toposequence (same macroclimate, same biota, same parent rock, but different parts of a hillslope or catena: crest, shoulder, sideslope, footslope, toeslope);
- soils representing a climosequence (same biota, same rock, same catena position, but different macroclimate zones); or
- soils representing a lithosequence (same macroclimate, same biota, same catena position, but different parent rock).

Although the research team was able to analyze and characterize soil samples from Cambodia and Jordan, and hypothesize about effects of environmental characteristics on the sample mines, the small number of *same* mine types did not allow comparative techniques that might have been able to isolate critical factors affecting landmines within an environment with scientific confidence.

CONCLUSIONS AND RECOMMENDATIONS

- **Greater number of matched soil/landmine pairs (functioning and not functioning).** This project has benefited from a substantial investment in planning, site visits to Cambodia and Jordan, landmine part and soil characterization, analyses, and report preparation. In fact, this study benefited from the collection of 6 PMN landmine/soil pairs, half of which were deemed ‘functional’ and the other half ‘not functional.’ This enabled us to compare soil properties associated with examples of the same landmine deemed to represent two parts of a ‘functionality continuum.’

However, a comparable future investment might yield clearer results if country- or region-specific landmines such as the PMN or M14 can be targeted, with the goal of characterizing **more landmine/soil pairs**, even if these samples represent a smaller overall sampling of all possible landmine/soil pairs. As one specific example, if more PMN landmines are collected from a greater variety of environmental settings (top of a hillslope, middle of a hillslope, bottom of a hillslope), greater insights into the role of soils in landmine aging may be possible.

Additionally, more matched landmine/soil pairs in future research are recommended, including both functional and likely-not-functional samples. As an example of the challenge faced in the current research phase related to this pairing, the M19 from Jordan was deemed functional, and was associated with soils with a very high carbon-to-nitrogen (C:N) ratio (33.3). This high C:N would suggest that microbial activity might be more limited, and therefore less likely to produce acidity capable of corroding this landmine, but in the absence of other M19 landmine/soil pairs deemed ‘not functional’ this conclusion would be tenuous at best.

- **Retaining of soils for future research.** Per our US Department of Agriculture foreign soil permit, we are only allowed to retain foreign soils for a period of <1 year. The JMU Soils Lab research team have begun the process of requesting an official extension, so that as our findings are disseminated (2 posters at national meetings in 2010, and a peer-reviewed manuscript expected to be in press in 2011), some of the remaining sample material will be available to interested parties for follow-on analyses.
- **Strategic expansion of locations for comparative advantage.** Commentary from preliminary presentation of soils analysis results at two conference events highlights feedback from peers that has indicated future areas of research related to new locations in order to maximize understanding of current sample analysis. One recommendation is to investigate the potential for characterizing landmine components and soils associated with minefields similar to our current research (e.g., Israeli samples, which could profitably be compared with Jordan samples, due to potentially similar climates and soils). The second is to investigate other southeast Asian minefields, where landmine emplacement might reflect different region-specific conflicts, thus enabling ‘time-stamping’ of landmine aging trajectories, if the same landmines can be characterized (e.g., PMN). For example, conflicts in Cambodia, Laos, and Vietnam have led to the creation of minefields that may hold the same landmine types, but laid at different times—all with potentially comparable climates

and soils. Characterization of PMN landmines that were emplaced in similar soils during different time periods might profitably help clarify the trajectories of landmine aging.

- **Increased, strategic collection of global field data.** While the research team had some success in acquiring shapefiles of mine clearance data, a much greater level of cooperation would help leverage and extrapolate our current results. For example, records of where potential ‘functional’ vs. ‘non-functional’ landmines were found can be cross-referenced with georeferenced geochemical databases, as well as indices of degradation vulnerability such as that developed by Colin King, to derive estimates of landmine aging trajectories.

In order to make the Aging Study research findings relevant to non-governmental as well as governmental organizations, it is critical to collect whatever available data there is including: where (precisely) mines have been cleared from and where they remain to be cleared from; the density of landmines encountered; some assessment of their presumed functionality (=‘age’); some indication of the timing of deployment of the landmines; landmine specifics (e.g., mine type, so that we can cross-index its initial vulnerability index value); and finally any environmental characteristics.

- The research team acknowledges these data are difficult to obtain under the most ideal of circumstances, but believe greater coordination with clearance organizations will greatly facilitate the collection of data that can assist in the determination of environmental conditions associated with landmines defined to be of a certain functionality. This is evidenced in a proposed field form developed by the larger research team during this phase of research (found in *Annex K*).
- **Aging Landmines Data Repository.** Mine clearance efforts represent a tremendous investment of financial and human resources; part of the return on this investment is a stream of very rich data. Unfortunately much of this return on the initial and continuing (mine risk education, for example) investment is never realized because there is no good repository for these streams of data, nor are rudimentary quality control measures in place for filtering those streams of data. As mine clearance funding evaporates, much greater returns on (increasingly smaller) investments in mine clearance could be achieved through a very modest investment in further exploration of the ways and rates at which landmines age and cease to function as intended.

If science-based allocation of scarce mine clearance resources (human, financial) is a local, regional, national, or international priority, this goal can only be achieved at minimum expense through a systematic effort to capture and make available data. Until these data are broadly available for meta-analyses by third parties, mine clearance progress will be limited to very small-scale studies such as this one to help prioritize mine clearance strategies. With greater data, patterns and extrapolation of landmine aging trends can be more confidently and accurately found and used to advantage in humanitarian mine action.

J. Full Summary of Report on Aging Study Implications, Prioritization and Decision-making Tool

1. Development of a prioritization and decision-making tool

One of the objectives of the current Landmine Aging Study was to develop a working framework or tool to assist WRA with prioritization of area clearance.⁵⁷ The project has done so, but it is important to recognize that the full potential of such tools will only be developed with the incorporation of more field data, from more locations and in respect of more mine types. One of the main recommendations of this project is that field organizations should be strongly encouraged to report the external condition of landmines discovered during clearance.

The aging process in landmines is complex and has different implications for different organizations, individuals and groups. Over time, and as more data become available, it may be feasible to develop a number of different tools of considerable sophistication. For example, it is possible to develop initial tools which can be used to relate aging information to practical situations faced by policy makers and planners. And while ideal, it is not yet possible to provide users with a tool that can accept direct field-collected data and yield an immediate, valid, output.

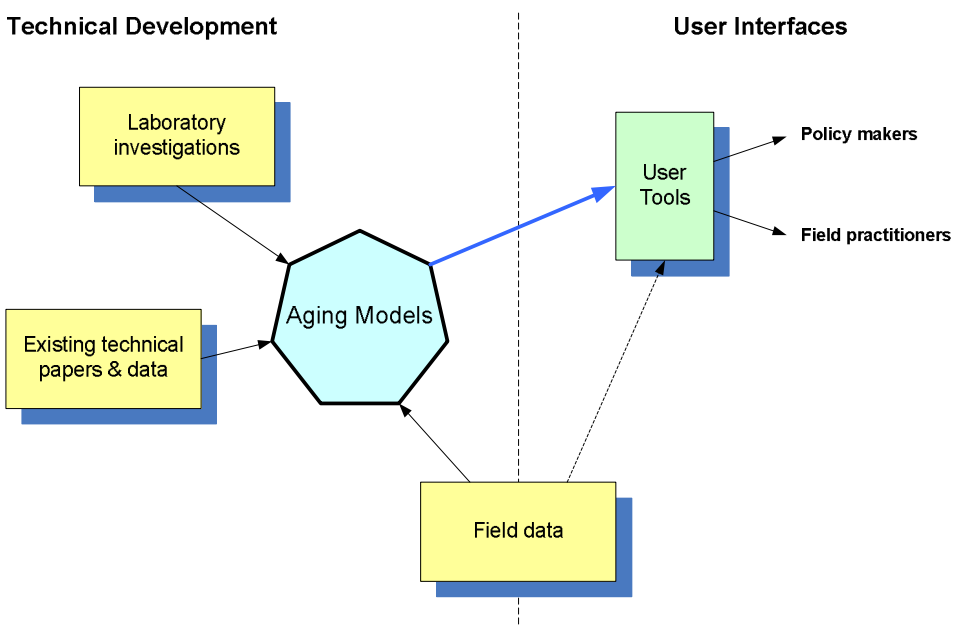


Figure 1. Relationship between data, models and user tools.

Figure 1 illustrates the approach adopted within the project. The project team has access to:

- **Field data** collected directly by project team researchers;
- The results of **laboratory investigations** carried out as part of the project; and

⁵⁷ Outcome #4 includes - A working framework or tool created for WRA to incorporate Phase 2, Year 1 findings to assist WRA with prioritization and decision-making in mine-action, and an explanation of how the framework was developed and how it can be used, as well as any potential limitations in use/applicability or relevant caveats.

- Information collected from existing **technical papers** published elsewhere.

Models are used to understand, assimilate and interpret the available information. **User tools** are developed reflecting the outcomes from the modeling processes.

In some cases it may be possible to establish a direct link between field data and user tools although doing so would require appropriate aging models to be integrated directly into the user tools. It is not possible to do so now and it is not clear how often such a feature might be important in practice at ground level.

The project statement of work focused on the potential for a framework or tool to help with prioritization and decision-making; however, developing such a tool requires the construction of a clear and coherent picture of the overall aging process and can bring some additional benefits including:

- Development of a clearer understanding of the way in which the various factors and influences associated with landmine aging relate to each other;
- Identification of those factors that are likely to be the most significant;
- A better understanding of the potential to extrapolate results between mine types and conditions.

2. Aging models

The project sought to develop models to describe different aspects of the aging process. The models were not created to act as tools for prioritization and decision-making in their own right, but rather to help in the development of user-friendly tools. It is important to keep in mind this differentiation between aging models and the tools developed for users. The models are not a stand-alone system suitable for direct use by non-technical personnel at this stage.

Two types of models were developed within the project. The first was a **diagrammatic description** of the various factors likely to be of significance using an influence diagram. The purpose of this model was to help identify how the different activities within the project related to each other and to identify the various related technical subjects and academic disciplines which might be important for the development of useful landmine aging models.

Secondly, a more narrowly defined influence diagram was used as the basis for a **simple simulation** of landmine aging processes. This type of representation can be used to model the way in which an individual landmine might change over time, so helping to understand how aging factors influence each other and which factors are likely to be of the greatest significance. This type of representation can also be used to model the likely effects of aging on a number of mines, much as the effects of age on a population of people can be modeled.

The aging model was developed using Vensim® a dynamic modeling software package developed by Ventana System Inc of Harvard, Massachusetts.⁵⁸ The software is widely used in industrial, economic, academic and military circles for the modeling of complex systems.

⁵⁸ Additional information is available at <http://vensim.com>.

2.1. Descriptor model

The initial aging influence diagram was developed by capturing existing ideas from the project technical specialist and then allowing the model to extend into related subjects.

It was clear from an early stage that it would not be possible to map and model the full extent of the possible system, which would encompass large areas of soil science, climatic effects, materials science, biology and chemistry. **Figure 2** illustrates the process from the initial identification of components of importance in the mine through the expansion of the diagram to incorporate a range of physical, environmental and climatic factors. The process demonstrates the extent to which ‘mission creep’ can lead to the inclusion of an exceptionally wide-ranging group of factors. There is great value in being aware of the extent of the influences relating to landmine aging, but pragmatic decision-making must take place to ensure that project activity remains within clear, achievable boundaries. Nevertheless, there are areas within all these disciplines which may justify further review and research in any future extension of the landmine aging study.

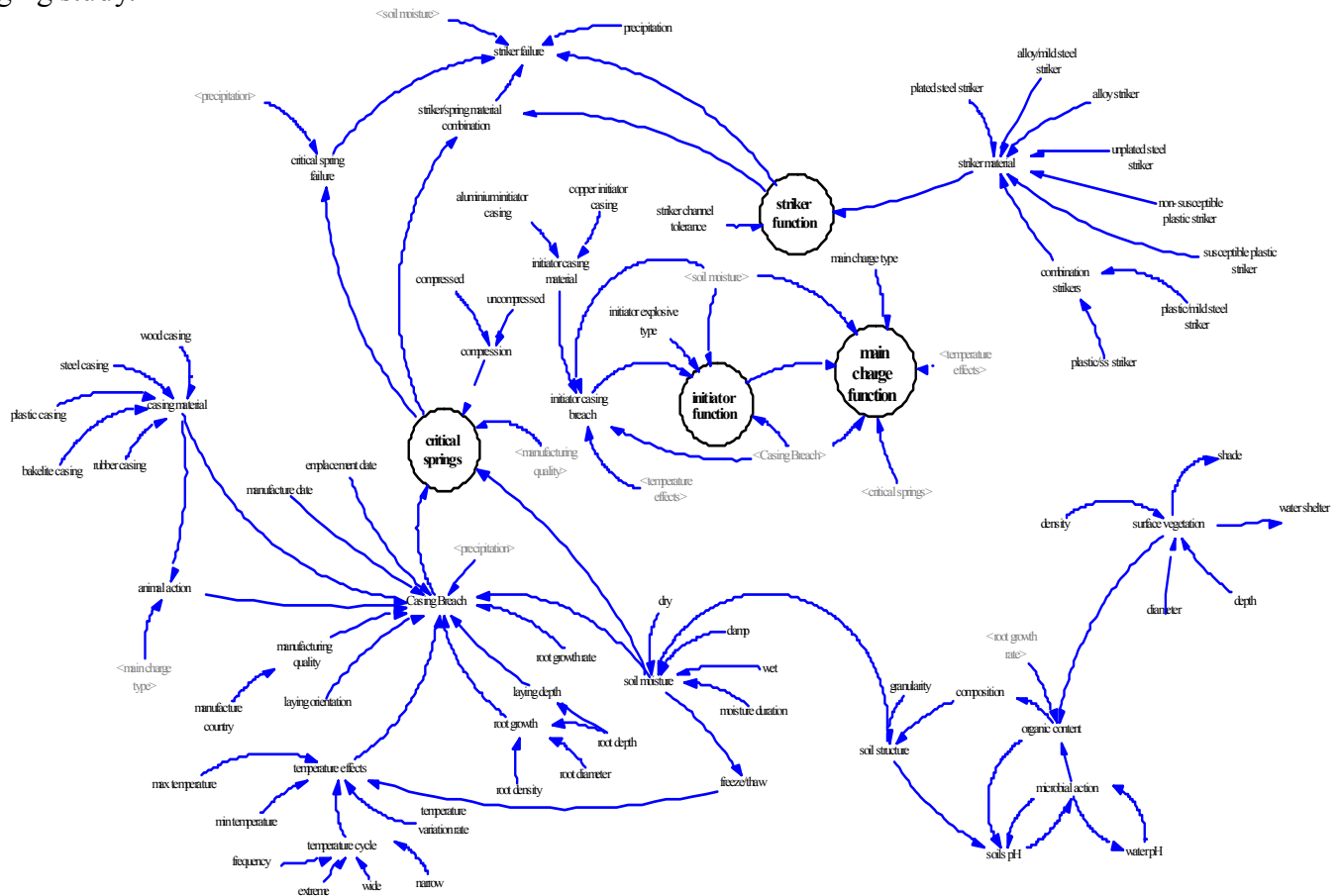


Figure 2. Initial landmine aging influence diagram (ID)

The descriptor model was developed as part of the internal project process, but the use of this and similar influence diagrams will provide important input in future work to develop aging models and user tools further.

2.2. Simulator model

2.2.1. Structure of the model

Development of the descriptor model showed how difficult it would be to develop a universal model of landmine aging. Instead it was decided to confine this stage of the modeling process to one type of landmine and to restrict environmental inputs of the model to general assessments of the lifespan of individual components of the mine.

The mine type selected for the initial model was the PMN. The decision was taken on the basis that:

- The PMN is a widely used mine, in basic numerical terms and in geographical spread;
- A number of copies of the PMN exhibit similar aging characteristics;
- The team had first-hand field information relating to the PMN;
- It was feasible to develop a model within the project's time and budget constraints.

The model was developed around the basic firing train⁵⁹ of the mine, one which is relatively straightforward and which exhibits characteristics found in many different mine types. **Figure 3** shows the sequence.

The key feature of a firing train is that it must fully operate as designed. If any one step does not happen then the overall sequence will be broken and the mine will not function as intended. The model described the process through six key steps:

1. Plunger function
2. Spring function
3. Striker function
4. Stab receptor function
5. Initiator function
6. Main charge function

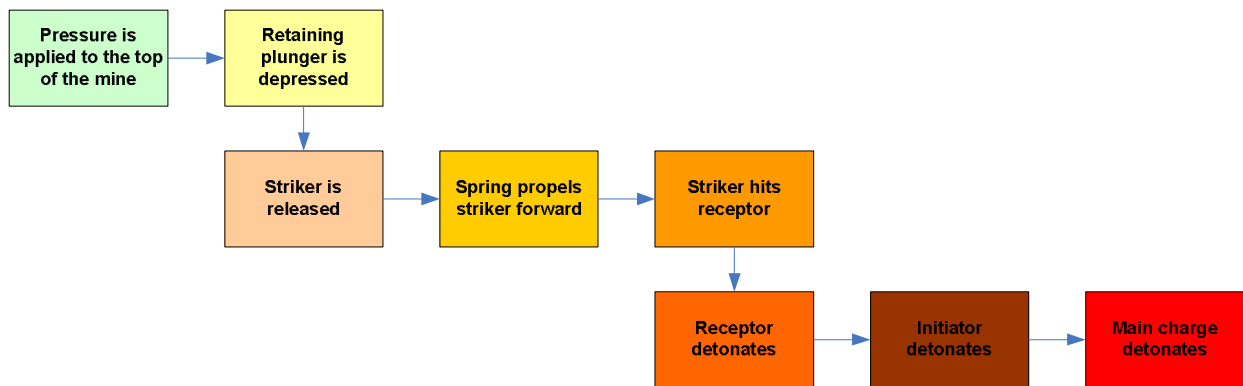


Figure 3. PMN Firing Train

⁵⁹ The firing train is the sequence of events leading from the initial victim trigger through fuzes, strikers, detonators and the main charge leading to the eventual explosion of the device.

For each step in the process the model considered the primary mechanisms which would prevent correct function. These include:

- Plunger obstruction
- Plunger degradation
- Spring obstruction
- Spring degradation
- Striker obstruction
- Striker degradation
- Stab receptor degradation
- Booster degradation
- Main charge degradation

The model recognizes that some other events may be of significance even though they are not in themselves part of the firing train.⁶⁰ Of these the most important is ‘casing breach,’ which includes, for the PMN, rupture of the rubber cover.

Ingress of water is known to be an accelerator of most aging 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 aging processes. The influence diagram capturing these various steps and factors is shown in **Figure 3**.

2.2.2. Modeling assumptions

The model draws on two key simplifying assumptions. First, it assumes that all changes in components as they age happen in a linear way; that is, the rate of deterioration of a component always stays the same. Where something changes the aging rate (such as when a breach of the mine casing allows water inside) then the new aging rate is also linear.

Figure 4 shows how a component, in this case a spring, changes over time from its starting status of 0 degradation towards a failed condition, when degradation reaches 1. To begin with, degradation occurs in a linear way at a low gradient until after 60 months when the casing of the mine is breached. After breach, degradation continues at a higher rate until failure occurs when the degradation level reaches 1.

⁶⁰ The Vulnerability Index (VI) tables described in the user tools section of this report makes use of those factors which were established to be of the greatest significance in the mine aging process. The aging model includes additional factors which are important for an understanding of the overall process, but which are of lesser importance from the perspective of the practical or policy tool user.

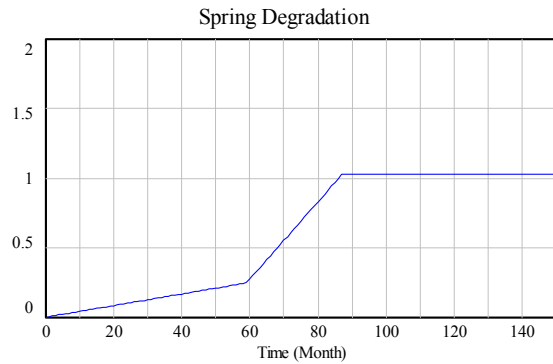


Figure 4. Linear deterioration rates before and after casing breach



Figure 5. Example probability of failure profile over time

Although degradation happens more quickly after casing breach, rates before and after breach are linear. It is likely that in reality degradation rates are not linear, but further data are required before different functions are adopted. For the purposes of this project the adoption of linear aging change relationships was not critical to the conclusions reached.

Second, the model assumes that when components of the mine fail they do so following a normal probability distribution (**Figure 5**); a small number of examples of the component fail early on in some mines, most fail around the average life expectancy of the component and a few examples continue to function for a much longer period of time.

Where more than one component is involved the failure, probabilities may occur over different time spans, but the failure profile for each component will follow its own normal distribution curve, as in **Figure 6**.

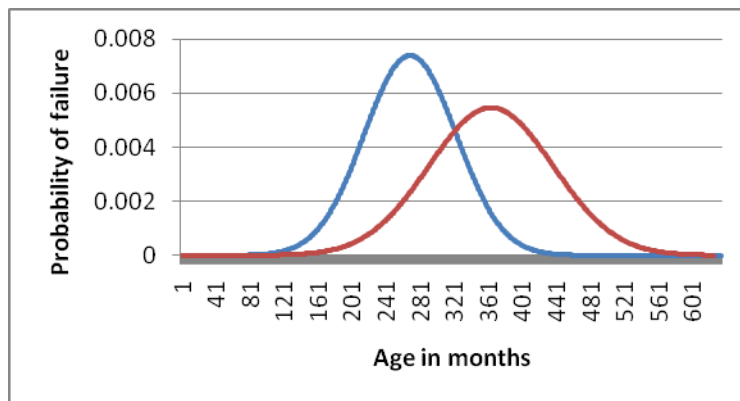


Figure 6. Illustrative failure curves for two components

The model assumes that the failure of any critical component constitutes a failure of the mine as a whole. This is the ‘first past the post’ principle. The cumulative effect as multiple components age and fail is that it becomes more and more likely that the mine will fail, even if one of its critical components happens to survive for an unusually long period.

The individual mine aging model functions on an essentially binary level; that is, a component either works or it doesn't. Over time its status changes in a linear fashion until it reaches the point at which it fails. Failure is assumed to be permanent.

Where a factor changes, such as when the casing breaches, it has an instantaneous effect on others factors that it influences (as illustrated in *Figure 3*).

2.2.3. Model functions

The model can be modified to investigate two aspects of landmine aging. First, it can be used to simulate the effects of aging on a single mine, helping to identify the relationships between the different components and the implications of deterioration in one part of the mine on other parts. This approach is likely to prove of value as more technical data becomes available from further laboratory investigations into the detail of how components fail over time. It may also be important in investigating more complex mines (such as bounding mines) which have more interacting components.

Alternatively, the model can be configured to look at the effects of aging on a population of mines, indicating the rate at which mines within that population may fail and so projecting a duration for mine impact and presence a country or region.

2.2.4. Model inputs

In due course it will be possible to determine volume of information available currently is small, but it would be possible to collect a substantial and potentially significant body of data on the basis of ongoing reporting from field programs.

2.2.5. Outputs

Where the effects of aging on an individual illustrative mine are concerned, the model provides graphical outputs showing how the various components and factors change over time. the various aging rates on the basis of scientific evidence and field data. At this stage there is not enough data to do so, although future literary reviews may identify relevant data from materials and soil sciences which could be valid.

The primary inputs to the model are estimates of the likely life span of different components under different conditions, based upon the experience and observations of field operators.

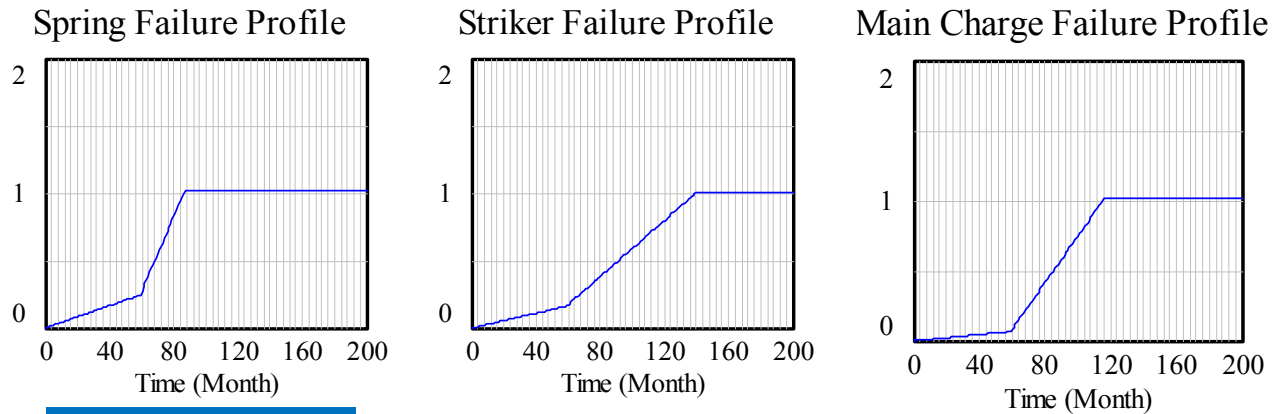


Figure 7. Illustrative component degradation profiles

Figure 7 illustrates typical output profiles for different components. In this example the casing breaches after 60 months (leading to the sharp increase in degradation rates for the different components) until each component eventually fails. In this case the spring is the first critical component to fail (after 80 months) and is the first past the post. The other components continue to degrade until they themselves fail, but the mine ceased functioning when the first critical component (the spring) failed.

For consideration of failures in a population of mines the model provides a cumulative probability curve illustrating the first past the post impact upon the proportion of mines which have failed.

2.2.6. Limitations

The primary limitations of the model are those imposed by the **availability of data**. The various rates of change used in the model are based upon informed estimation rather than experimental or empirical data.

The model does not currently model situations in which degradation might have the effect of making the mine **more sensitive and more likely to explode**. Based upon field experience and data collected to date, the project team assessment is that this situation is very rare.

Nevertheless, it is entirely possible to model such situations should it become useful to do so.

3. Discussion

Development of the descriptive and simulation models raised a number of important points for consideration.

3.1. Supply and demand in the firing sequence

The model is based upon the fact that at each step in the sequence of events, leading from actuation by a victim through to detonation of the main charge, enough energy must be supplied by the preceding step to satisfy the demands of the next step. The spring must provide enough stored energy to accelerate the striker, with enough force, to activate the stab receptor which

must detonate, releasing enough energy, to trigger the booster charge which must in turn detonate, and release enough energy, to trigger the main charge.

Changes over time can affect both sides of the balance at each stage—a degraded spring may no longer have the mechanical properties necessary to deliver enough energy to the striker. At the same time the striker may have corroded and expanded into its housing such that it now requires more energy to achieve the necessary velocity to set off the stab receptor.

It is also possible that some changes over time may create a situation where less energy is required to satisfy the demands of one of the steps in the process. This situation would correspond to one in which the mine might become more, rather than less, sensitive as it ages.⁶¹ And it is possible to envisage a sequence of events in which the mine becomes less sensitive over time, then goes through a period where its function is fully restored, before finally becoming less sensitive and finally entirely non-functional. One example would be a mine that incorporated an ignition composition which became damp, but then dried out again.

The value of adopting a ‘supply and demand’ approach to the sequence of events is that it may offer the prospect of being able to define levels of energy required within the system; this can permit the delegation of some research activities to laboratories which would not need to have a full understanding of the overall subject of landmine aging. Thus, if the amount of energy that must be stored in a spring of known dimensions, made from a defined grade of steel, required to propel a striker with at least the minimum required velocity to set off a stab receptor can be determined, then it should be possible to access existing research work into the changes in the properties of that type of steel.

A good deal of such work has been carried out in other sectors, especially the automotive and aviation industries. Much of the existing data is likely to be valid for the purposes of this project, but it is still necessary to establish how to extrapolate between applications and circumstances. The establishment of specific energy requirements for each step would be a useful step in allowing for the importation of such existing material, and for the definition of research requirements for other participants in this study in the future.

3.2. Points of vulnerability in the firing sequence

A mine becomes non-functioning when one or more of the steps in the process cannot take place—essentially when the previous step cannot satisfy the energy demand of the subsequent step. What is readily apparent is that not all the steps are not equally vulnerable to disruption. In the example of the PMN the main points of vulnerability are the following:

- The plunger becomes obstructed and can no longer be depressed.
- The striker spring becomes degraded and does not propel the striker forward.
- The striker becomes obstructed in its housing channel, either through ingress of outside material (soil) or through corrosion resulting in its own expansion in diameter.

⁶¹ It is worth reiterating that this situation appears to be extremely rare, although it would be possible to model and investigate such scenarios in more detail if specific circumstances ever suggested that it was important to do so.

- The striker becomes degraded such that it can no longer impact properly with the stab receptor (either it becomes too blunt to penetrate the stab receptor cover or it may become too fragile to remain intact on impact⁶²).
- The stab receptor degrades so that it does not detonate.
- The booster charge degrades so that it no longer detonates.
- The main charge degrades so that it no longer detonates.

The limited evidence available so far suggests that the striker spring is a more vulnerable component than the striker itself. Similarly it is less likely that the plunger will become obstructed. Unless there is a major fracturing of the outer casing it would appear that the metal components are likely to degrade faster than the explosive components, although the stab receptor is likely to be much more vulnerable than the booster or main explosive charges.

More research is required to understand better how explosive changes over time and how those changes affect the ease with which it will detonate, but it is already clear that some elements of the aging model merit more attention than others.

3.3. Age neutralization and age disarmament

The way that components fail is of fundamental importance to the technical questions of landmine aging, but which ones fail and in which order may be of wider significance. As different components fail they may interrupt the firing train in different ways mirroring the existing technical processes of neutralization and disarmament.

Neutralization is the process of preventing the firing train from functioning, typically through some mechanical interference, such as the presence of a safety pin, within the designed sequence. A neutralized mine remains complete in all respects, but the firing sequence is prevented from running through its normal functions.

Disarmament occurs when an element in the explosive train is physically removed from the device. Under these circumstances the mine cannot function since there is a gap in the intended sequence. Disarmament would be achieved in a PMN by removing the booster charge (which incorporates the stab receptor). Even if the stab receptor were present, the mechanical sequence of plunger movement, striker release and acceleration under the force of the spring could all take place, with the striker hitting the stab receptor and the receptor igniting as intended, but the process would then stop. There would be no mechanism for the energy released by the stab receptor to trigger the main charge. Washout of explosive content in a mine immersed in water would be an alternative example of mine disarmament.

A mine *neutralized* through aging could, under some circumstances, become functional once again. If neutralization was achieved by an obstruction to a component and that obstruction was then washed away, the mine might regain the ability to function. A mine *disarmed* though aging is highly unlikely to become functional again.

⁶² In some circumstances degradation and corrosion of striker pins can mean that the striker no longer reaches the stab receptor when it is propelled forward.

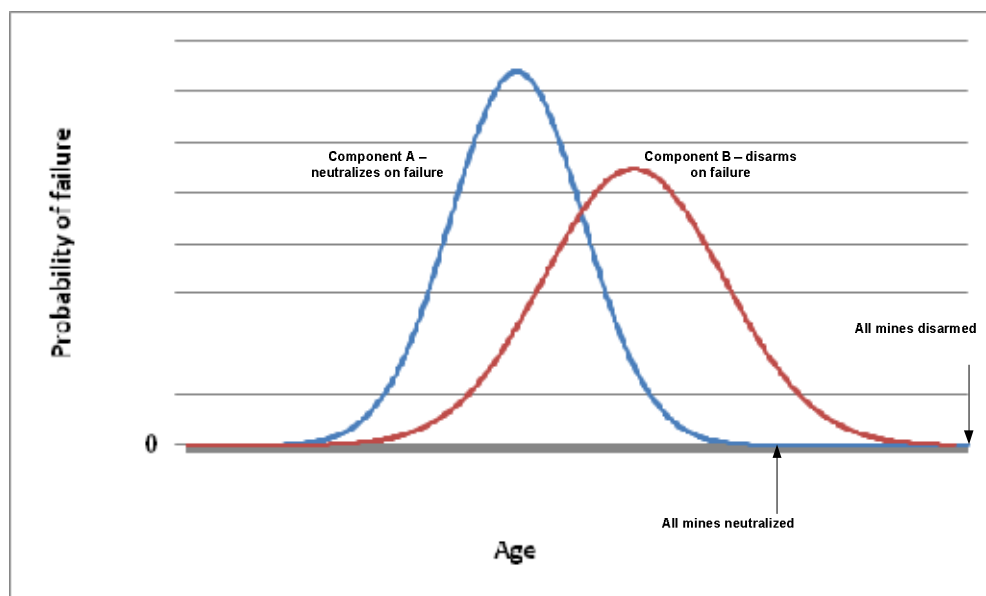


Figure 8. Neutralization and failure in an illustrative mine population

The aging model might indicate that the population of a particular type of mine, in a given country, could be expected to have become wholly non-functional after a certain passage of time. **Figure 8** illustrates a situation in which failure involves two components. Component A is a component, the failure of which results in the neutralization of the mine. Component B causes disarmament when it fails. The overall failure of the mine occurs on the basis of the first past the post principle—that is, whatever component fails first renders the mine non-functional. However, if that failure corresponds to age-neutralization then it could be argued that the device remains potentially hazardous. Only when a population of mines can be expected to have become fully age-disarmed can it be said that any hazard has finally, and permanently, disappeared.

Such questions present important challenges for policy makers as well as for field planners and practitioners. The operator clearing mines may eventually take a view that the hazard associated with clearance of a particular type of mine has reached the point where it is effectively zero. It may be reasonable to believe that end-users of land are safe from the threat of that type of mine. At the same time policy makers may feel that compliance with international agreements and conventions demand the removal of the devices, even if, arguably, they are no longer mines.

These may seem like academic points for consideration by some future generation of decision-makers. However, these are pressing issues since some landmine types in some countries are already close to the point where they could be considered ‘non-hazardous’; in some cases, it could be argued that they no longer constitute landmines within the accepted definitions.

4. User tools

The modeling process gave rise to two tools for users. These are:

- Vulnerability index tables

- Mine lifespan charts

Vulnerability Index tables are intended to help operational planners to understand the susceptibility of different mine types to aging processes and so identify which mine types are likely to remain hazardous for longer.

Mine lifespan charts are primarily for higher level decision makers interested in understanding the longer term duration of mine presence in a country, and the significance of that presence both as a hazard and in terms of compliance with international conventions.

4.1. Vulnerability Index (VI) tables for Landmine Aging Study materials and mines

The current phase of research began to rigorously identify the importance of individual mine components on the firing train and, thus, the ability of a mine to function in the way intended. Taking it a step further, to understand how a mine's 'out-of-box' functionality is impacted when any one component changes, the team coupled materials identification with each mine component. Using field observations of specific mines, the team developed the Vulnerability Index concept, in which major components of mines are listed and the known or suspected material(s) of that mine component are identified.

4.1.1. Material vulnerability ranking

Materials were then ranked according to 'resilience' to degradation, based on known chemical and materials science principles and research findings (**Table 1**). Within JMU, the Chemistry Department research team began scientifically identifying materials from sample mines and providing data on known or potential degradation processes (*see Annex G, H*). **Table 1** shows the most common non-explosive materials used in mines, ranked from the least vulnerable (such as composites and stainless steel) to the most vulnerable (such as rubber and wood). Since the exposure of surface area is a critical factor, the thickness of some materials is also taken into account. Each material listed in **Table 1** has then been allocated an abbreviation for convenience.

4.1.2. Component vulnerability index

There are two categories of mine component that are significant for the effects of aging; these are:

- Components critical to operation;
- Components critical to the integrity of the mine.

Components critical to operation will normally include the major elements of the fuzing system and of the explosive train. Removal or non-functioning of one of these components will normally render the mine incapable of functioning as intended.

Components critical to the integrity of the mine normally include the casing, along with assemblies (such as covers and plugs) that seal the casing.

Some components may fall into both categories, such as the casing of a box mine, which also provides the means of fuze actuation.

Not all of the components that fall into the above categories need be considered. This is because some are inherently less vulnerable than others. For example, many mines contain a booster that is critical to correct function; however, the booster is invariably composed of resilient high explosive and is located in a protected position. Field observation and common sense dictates that the initiator or main charge will fail before the booster. Similar principles apply to other components, such as sealing plugs.

Table 2 lists the most significant components, along with the materials normally used, and allocates them a rating from 1 (least vulnerable) to 5 (most vulnerable), according to **Table 1**.

4.1.3. Vulnerability of mines

Table 3 shows mines examined during the study and rates their critical components according to the contents of **Tables 1** and **2**. The total of the various Component Vulnerability Indexes yields a **Vulnerability Index (VI)** for each type of mine. The higher the VI, the more prone to degradation as it ages; the lower the figure, the more resilient the mine is likely to be. For example, the PMN's casing is identified as highly resistant to degradation (1), but its rubber cover is relatively more vulnerable to degradation effects (4); the PMN's total VI was calculated as 19, out of a possible score of 35.

The VI only accounts for the vulnerability of the materials within the mine; however a number of other factors may contribute to its degradation. These include the degree to which it is watertight, the tightness of internal tolerances and its position (i.e., above-ground, flush with the surface or buried). These additional factors can be used to weight the VI in order to make a more realistic assessment of the aging effects.

4.1.4. Mine comparisons

Table 4 indicates the applicability of the VI to other mines. Along with the 14 mines listed in **Table 3** are three further categories:

- **Same structure:** this means that the materials, construction and characteristics would be close enough to yield an identical VI. Direct copies, licensed versions or close variants fall into this category. Twenty mines are listed, of which 5 are believed to have been used in significant numbers.
- **Similar structure:** mines that share most of the characteristics of the mines examined in the study. These mines incorporate technical variations that would not significantly alter their aging characteristics. The VI for these mines could be expected to be within 2 points of the original. Twelve mines are listed, all of which are believed to have been used in significant numbers.
- **Some similarity:** these are mines that have significantly different designs, yet share enough characteristics for the VI to have some validity. It is likely that the VI for these mines would be within 4 points of the original (though some may be closer, or even the

same). Forty-seven mines are listed, of which 35 are believed to have been used in significant numbers.

4.1.5. Modifiers

The Vulnerability Index represents a significant but rough first step at quantifying the measurement of vulnerability to degrade and change over time for both a complete mine and its major components. However, further field analysis, testing and collection of data to support this model is required in order to develop a refined tool that can be used with confidence.

One challenge is understanding the impact of microenvironmental differences for same mine types on mines in varying locations. A first attempt to answer this question, undertaken by the JMU Department of Geology and Environmental Science, was hampered by uncontrollable factors related to landmines recovered from the field—namely, the lack of same mine types in our two locations. Even so, broad observations pointed to significant differences in degradation based on environment; this observation is supported by anecdotal field expertise and supplemental mine analysis conducted in the Falklands and other countries during the course of this research.

As indicated by the ‘Modifiers’ listed in **Table 3**, the team has identified the importance of external variables in the consideration of Vulnerability Index. As is discussed later in Section 5.4, future research should further explore the potential equation developed in the current Aging Study research effort:

$$\text{LMR} = \text{VI} * \text{E} / \text{T} \text{ (Live Mine Risk} = [\text{Vulnerability Index} * \text{Environment}] / \text{Time})$$

Due to current research phase limitations and the need for matched landmine/soil pairing across different locations, this concept remains to be further explored and tested in future phases of research on landmine aging. Even the concept of ‘environment’ as such required nuanced approaches to understanding and measuring a mine’s VI within a certain context (e.g., water, UV, soil).

VI is currently a low-resolution model which provides a means to understand the relative vulnerability to degradation of different mines. The model can be refined by further work on the ranking of materials (types and thicknesses) and examination of weighting factors.

Table 1. Materials and resilience to degradation

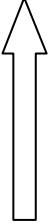
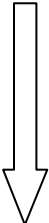
Materials list		Abbreviation	Notes
<p>Higher</p>  <p>RESILIENCE</p>  <p>Lower</p>	Epoxy composite	EC	<p>6. 'Resilience' ranking is based on field observation of deterioration through aging.</p> <p>7. <i>NA</i> (not applicable) used where component is absent</p> <p>8. Boosters are not considered because they will be the same as, or higher quality than, main charge rating 1</p> <p>9. Initiators may be percussion or stab-sensitive, in AL or CU capsules or tubes, but all are vulnerable through their thin seals (generally foil, gauze or lacquer). VI, therefore, is mainly determined by their position rather than their construction.</p> <p>10. Where striker is absent, use same VI as Firing pin</p>
	FiberGlass	FG	
	Bakelite (or thermosetting plastic)	B	
	Stainless steel – thick (> 1 mm)	SS+	
	Stainless steel – thin (<1 mm)	SS	
	Copper	CU	
	Polycarbonate and Acetates	PC	
	Thermoplastic - thick (>1 mm)	TP+	
	Thermoplastic - thin (<1 mm)	TP	
	Mild steel – plated or thick	MSP	
	Aluminum – thick (> 1 mm)	AL +	
	Aluminum – thin (<1 mm)	AL	
	Mild steel – unplated or thin	MSU	
	Rubber – thick (> 1 mm)	R+	
	Rubber – thin (<1 mm)	R	
	Wood	W	
	Cardboard	C	

Table 2. Component Vulnerability Index

Rating	Cover/top	Casing	Striker	Firing pin	Spring	Initiator	Main charge
1	B,FG	FG,B	SS+,PC	SS+,PC	EC,FG	Double encased capsule	Comp B, Tetryl, Pressed TNT
2	MSP, TP+	PC	SS,TP	SS,TP	SS/+	Well protected	Cast TNT – high grade
3	MSU	MSP,T P+	AL+	AL+	MSP	In internal void	Cast TNT – low grade
4	R+	MSU,T P	MSP	MSP	MSU	Vulnerable position	Soluble mixtures, LE
5	R, W	W	MSU	MSU	R/+	Little or no protection	HME

Table 3. Vulnerability of mines by type

COMPONENTS	MINE TYPES													
	PMN	PMN-2	PMD-6	M35	M14	M6	M15	M16	M19	MD-82B	P4 B	SB-33	SB-81	Type 72
Cover	4	4	5	2	2	2	2	4	1	2	3	4	2	5
Casing	1	3	5	3	3	3	3	4	1	3	3	2	2	3
Striker	4	3	4	2	4	4	4	4	1	5	2	1	1	4
Firing pin	4	4	4	2	4	4	4	4	1	5	1	1	1	4
Striker spring	3	3	3	2	1	3	3	3	1	4	3	3	3	1
Cap	2	3	5	2	2	2	2	4	2	4	1	2	2	3
Main charge	1	1	1	3	1	1	1	2	1	1	1	1	1	1
Vulnerability Index (VI)*	19	21	27	16	17	19	19	25	8	24	14	14	14	18

*Possible modifiers include environment, soil type and degree of exposure.

Table 4. Mine comparisons

MINE TYPES	VI	SAME STRUCTURE (Same VI)	SIMILAR STRUCTURE (VI +/- 2)	SOME SIMILARITY (VI +/- 4)
PMN	19	MS-3, Type 58, Iraqi PMN COPY	GYATA-64, PM-79	FMK-1
PMN-2	21			
PMD-6	27	PP Mi-D, TYPE 59, PMD-1		APP M57, PT Mi-D, TMD-44, TMD-B, ATM-44, TMD-1
M35	16		M409, MAPs, M411, M/969	PRB-M3
M14	17	Indian version (AP NM M14), M/56	MN-79	PP Mi-NA 1
M6/M15	19			M/71, Mk 7, No 6, Tellermine 35/42/43, TM-46/57/62M, TMM-1, Type 72 (Metallic), UKA-63
M16	25	Indian and South Korean versions	OZM-3, Type 69	DM-31, M2, M/966, No. 12, NR-442, OZM-72, PP Mi-Sr, P-S-1, PSM-1, S-mine
M19	8	Chilean, Iranian, South Korean and Turkish versions		
MD-82B	24			P2 Mk2, P4 Mk1
P4B	14	P4A	C3B	No. 10
SB-33	14	EM-20, M/412, P-5	MAUS, VS-MK2	TS-50, VAR/40, VS-50, YM-1, YM-1b
SB-81	12	M/453, YM-II		SH-55, TC/2.4, TC/3.6, TC/6, VS-1.6, VS-2.2, YM-III
Type 72	21			DM-11

4.2. Mine lifespan charts

The lifespan charts consider three key periods in the life of a mine contamination problem:

- Laying period—the time from when the first mine of the type is laid in a country or region, until the last mine of that type is laid;
- The lifespan of components that neutralize on failure;
- The lifespan of components that disarm on failure.

The first mines laid are expected to fail over time along a normal probability distribution. The last mines laid are expected to fail following the same failure probability curve.⁶³ In each case different components will fail along their own probability curves, some resulting in neutralization, some in disarmament.

In *Error! Reference source not found. 9*, the neutralization element of the bar covers the period until all components which neutralize on failure can be expected to have failed. The disarmament element correspondingly reflects the duration until all components which disarm on failure can be expected to have failed. For convenience the different elements of the bar can be overlaid, as shown in *Error! Reference source not found. 10*. In general it is expected that neutralizing components (springs, pins, etc.) will tend to fail before disarming (explosive) components. It is possible that in some mine types explosive elements will deteriorate and fail before neutralizing items.⁶⁴

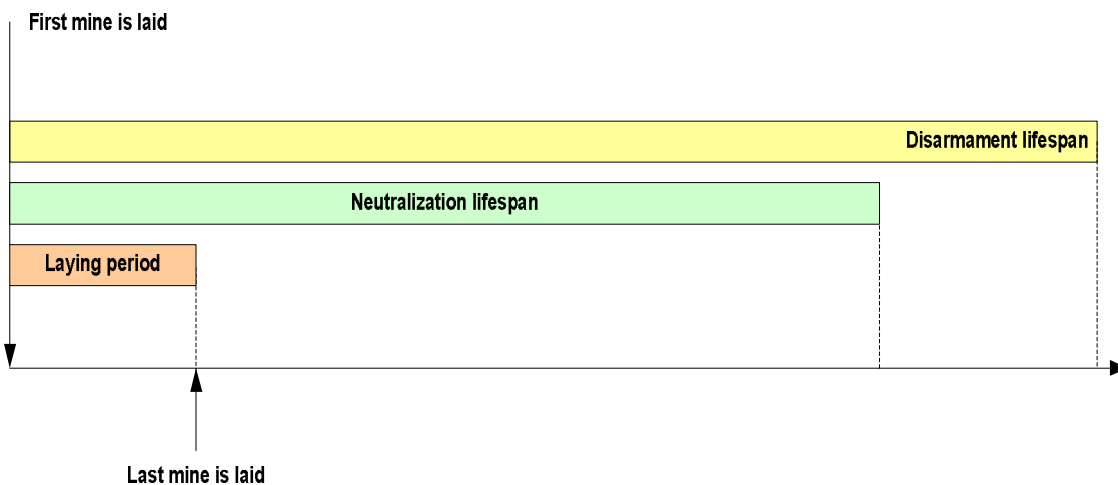


Figure 9 . Illustrative mine lifespan chart

⁶³ This means that the model does not take into account any degradation which might occur during the period between manufacture and placement into the ground. In some instances, poor storage conditions may be a significant factor in aging processes.

⁶⁴ A possible example of this situation could be found with PFM-1 mines where a casing breach would result in run-off or evaporation of the liquid explosive, while the metallic components of the firing train might remain in good condition.

Within an affected country it is likely that there will be several types of mine present. The overall chart for such a country would look as in **Figure 10**. For each type of mine (in this case three types; A, B and C) a lifespan bar indicates the history of the type from the period during which laying took place through to the projected end dates for both neutralization and disarmament.

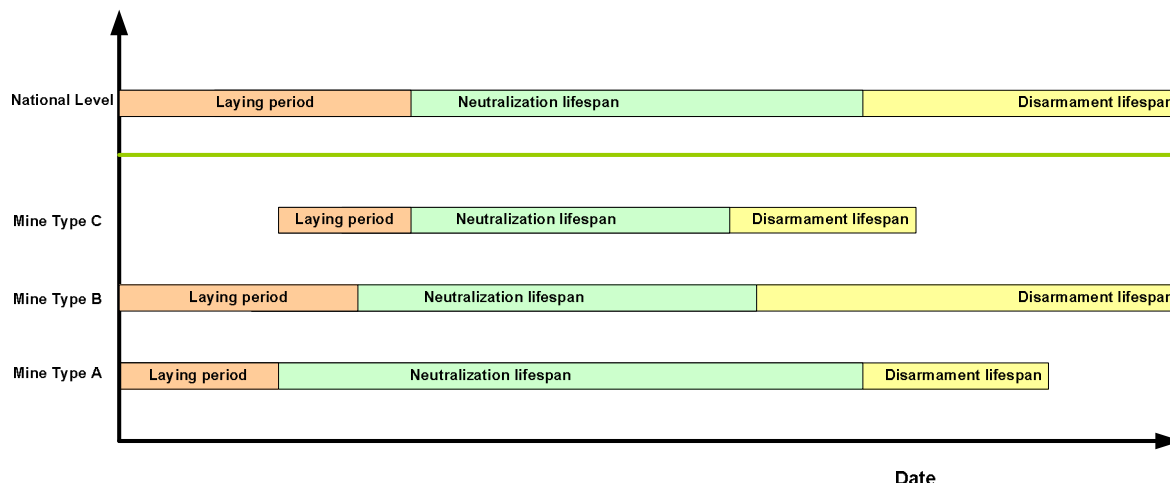


Figure 10. Illustrative country overview

At the national level the various subsidiary bars can be further aggregated to describe the overall national landmine contamination lifespan, through to the point at which it is unlikely that any landmines remain in an actual- or potential-functioning condition within the country.

The length of each bar is related to the vulnerability of the mine type under the environmental conditions found in the region where they are laid. At this stage there is no reliable mathematical relationship between the VI of a mine and the length of its lifespan, but it can be said with some confidence that mines with higher VIs will have shorter lifespans. Thus, in the illustration in **Figure 10** mine type C is likely to have a higher VI than mine type B.

It is also possible to extrapolate between types and regions to say that similar mine types, with similar VIs, are likely to respond to similar environmental conditions in similar ways; the lifespan bar of a wooden box mine in one hot wet environment is likely to be similar to that of another wooden cased mine in another hot, wet area. Mines that contain similar components (such as strikers and pins) manufactured from similar material can be expected to exhibit similar degradation and failure patterns.

4.3. Residual hazards

The lifespan chart considers the impact of aging on a population of landmines. Once all the mines have failed, either through disarmament or neutralization, the original population of mines no longer presents a hazard to victims in the way they were originally designed. However, it is important to note that some individual explosive components of the mines may still represent a general hazard to people. A mine may be unable to function as a mine, but if someone were to throw it onto a fire there might still be elements inside which could explode.

Evidence from areas fought over during World War I suggest that explosives can remain hazardous for extended periods (it is after all almost 100 years now since the battles of WWI). The fact that items may, arguably, no longer be ‘mines’ by definition does not in itself address the longer term implications associated with the presence of residual explosive material.

5. Current and future utility

The two user tools developed within the project have immediate value, but **both will benefit from expanded source data.**

- The existing mine vulnerability index tables can be refined as further data become available. Additional tables can be generated for other types.
- The lifespan charts will benefit from additional historical data in relation to when mines of different types were laid in affected countries and from the collection of data about the condition of mines when they are found during field clearance operations.

5.1. Use by policy makers

The lifespan chart would become a tool primarily for use by policy-makers. To fulfill its potential it now needs more input data from field operations around the world. It provides an overview of a mine contamination problem in a country and gives an indication of how long it is likely that mines will remain a direct hazard to the people of that country.

Policy makers may also wish to consider the implications of the lifespan chart for the longer term questions of residual capacity and compliance with applicable international law. It is generally accepted that after an intensive period of clearance operations there will come a time when all identified hazard areas have been dealt with. At the same time it is pragmatic to take a view that some mines may have gone unnoticed. The question of residual capacity is becoming an important one in mine action forums. Better assessments of landmine lifespans will help to inform policy makers about likely residual capacity needs.

A more contentious question may be that of compliance with international law. It is not the objective of this project to become involved in the fine detail of legal discussions about compliance, but it is important to highlight the fact that aging issues may be significant in this context. Very few countries have a well-enough defined landmine problem that they will reach a point when they will be able to say with absolute confidence that they have cleared each and every mine on their territory. Instead, accepted methods of survey are used to define the problem as well as possible so as to provide a definition against which final compliance with international law can be reasonably judged.

Even under circumstances where a country has reached an acceptable status to demonstrate compliance, there will be a period when any mines that might have escaped detection could, theoretically, remain viable. The aging study’s lifespan charts could provide a credible final point at which it can be said that, even should some mines have been missed, they can be

assumed to no longer represent contamination of the type addressed by the international legislation.

It should be restated that the question of when a mine might no longer be considered a mine is a contentious one, but this report is about identifying practical and pragmatic outcomes of use in the real world. The authors would not suggest that time should be substituted for action as a means of addressing landmine contamination problems; however, it is important to recognize that eventually time will destroy any items that have, for whatever reason, evaded the mine action industry.

5.2. Use by planners

The aging study has only considered a limited number of landmines and has only a limited body of data to work from. Nevertheless, it is already possible to highlight some issues which operational planners should take into account.

The first, and most important point, is that landmine aging is an issue today. It is not some hypothetical question which will only become significant in years or decades time. Some mine types in some regions are already at, or getting close to, the end of their lifespans. Other types are well advanced along the neutralization and disarmament profiles. Like all technical aspects of mine action it is important that we understand what is going on and use that knowledge to inform our decisions in practical terms.

On the basis of VI tables it is already possible to form some judgments about which mine types are likely to remain hazardous for longest. This is of significance in terms of advice to field operators, but also in instances where there may be a need to prioritize between different sites affected by different types of contamination. It is already possible to consider the implications of mine vulnerability within prioritization processes in some field programs. Over time, and as more field data is collected, it is likely that the importance of VI analysis and mine-lifespan charts for prioritization will increase.

5.3. Implications for field operators

It is much too early for the user tools developed in this project to be used as a direct input into site level operational planning. However, it is fair to say that the aging study raises important issues of relevance to field operators.

The first point once again is that landmine aging is an issue of relevance today. Some landmine populations in some countries are already close to the end of their lives. It is hard to find an example of any tripwire activated mine or a PMD-6 functioning in Cambodia today and there is anecdotal information to suggest that some other types in other countries are beginning to display the effects of aging on a significant proportion of their populations.⁶⁵

Secondly, it is clear that micro-environmental factors have great influence on how quickly a

⁶⁵ For example, there is some anecdotal evidence to suggest that a significant proportion of PFM-1 mines in Tajikistan are now non-functioning.

landmine deteriorates as it ages. However much an aging tool can provide indications about the likely state of typical examples of a mine under average conditions it will never be able to predict the condition of an individual mine in a particular patch of ground. However, work carried out by the project has already yielded information of direct importance to operators. In the case of the Russian PMD-6, the corroded condition of the mine led operators to believe that it would be especially sensitive and hard to deal with. In fact, investigation by the project team showed that the nature of the degradation had been to render the mine entirely non-functional (to disarm it). The conclusion was that the mine type was actually much less hazardous to deal with than had been suspected.

The study cannot yield such detailed conclusions on every type of mine, but the example highlights the importance of field operators taking an interest in the subject and doing what they can to help gather data. Further aging investigations will rely upon a great deal of statistical analysis, which can only be carried out in a useful way if there is as much raw data as possible to work from.

In particular, investigation to date suggests that the external condition of a mine is likely to be a good proxy indicator for its overall functionality. The report authors absolutely do not want to encourage field operators to dismantle mines to investigate the condition of their internal components, but they would encourage operators to get into the habit of recording (and reporting) the external conditions of mines when they are discovered. In particular, any holes, cracks or other breaches in the casing or cover of the mine are of great interest.

Statistical analysis of the proportions of mines of a given type suffering from such obvious damage will help greatly in making predictions about the likely overall lifespan of the type.

5.4. ‘Modifiers’ and their implications for future research

As indicated in **Table 3** and touched upon in Section 4.1., future research related to the Vulnerability Index and lifespan chart tools will need to address the impact of ‘modifiers’ on assumed rates of degradation, vulnerability of materials to degradation, and which components of a mine are first impacted by aging, to what end.

As the current phase of research was nearing its end, the research team explored how to most realistically include modifiers—particularly environmental—in the models of degradation. A proposed working equation to approach this dynamic relationship between mine components, materials, time and environment was developed:

$$\text{LMR} = \text{VI} * \text{E} / \text{T} \text{ (Live-Mine Risk} = [\text{Vulnerability Index} * \text{Environment}] / \text{Time})$$

In this equation, time is the denominator since as time increases—so long a landmine is exposed to environmental factors altering it from ‘factory’ condition—live-mine risk will ultimately decrease. This equation assumes the rate of degradation consists of three main factors, all interacting with each other in complex ways:

- Vulnerability Index (VI), our measure of how susceptible a given landmine type (or component therein) is to degradation based on *what* material it is made of; in essence, this

is a measure of the quality of the manufacture as well as the resistance of the materials comprising the landmine to degradation

- Environment, which can be a variety of forces, from soil aggressiveness (measured in terms of redox potential, pH, acidity, etc.), soil moisture content, rainfall, heat, cold, fires, shrink/swell soils, oceanic forces (i.e., saltwater degradation), plant interferences (i.e., roots), and even human impact⁶⁶; environment is the most dynamic variable and is the determinate of *how* mine materials and mine functionality will be affected and changed
- Time, which is the constant variable contributing to degradation, is essential for; for this reason it is crucial to understand the rates of landmine degradation in order to evaluate the outcomes and timeline of degradation and aging of mine components—*when* things might change

In other words, some or all of the environmental forces are directly responsible for the eventual degradation of landmines, and while the nature of the landmine components are fundamental in determining the ability of mines to resist the process of degradation, at the same the environmental effects are tantamount to what, and therefore how, a landmine will or will not resist a degradation process. Meanwhile, only with the passage of time can the environmental conditions affect landmines of greatly different manufacture and VI.

In future work, soil maps may be able to provide an index of soil aggression, arguably the most important ingredient in the environmental factor portion of VI*E/T. A paper focusing on soil and soil maps in Jordan⁶⁷ compared soil maps with pre-established criterion to accurately derive soil characteristics, and so was able to classify multiple features of interest. Such mapping work may be useful in establishing soil traits such as pH, which will give us a better predictive model of soil aggressiveness.

Due to current research phase limitations and the need for matched landmine/soil pairing across different locations, this concept remains to be further explored and tested in future phases of research on landmine aging. Even the concept of ‘environment’ as such required nuanced approaches to understanding and measuring a mine’s VI within a certain context (e.g., water, UV, soil). However, the ability to understand the variations in aging effects by environment will in the future contribute to an evermore refined understanding of landmine degradation, and can yield additional confidence in the models currently developed.

6. Conclusions

In more general terms, at the beginning of this project little was understood about landmine aging. As a result of the work done to date the situation has become a good deal clearer. While it is clear that more work needs to be done it is already apparent that landmine aging is of importance now, to field operators and to policymakers and planners.

Specifically, development of user tools has highlighted the following conclusions:

⁶⁶ Human land uses and activity can also be considered an environmental condition; if farmers are working a mined field, their agricultural practices (tools, fertilizers, compost, grazing animals) could also accelerate landmine degradation.

⁶⁷ See *Ziadat, 2007* in literature review section.

- Landmine aging is an issue now; it will become more and more important as time passes;
- The vulnerability of different mine types to degradation over time can be assessed and indexed;
- Further statistical analysis should help predict the likely lifespan of different mine types under various conditions;
- Policy makers should consider the implications of landmine aging for residual capacity and public health questions;
- Policy makers may wish to consider the implications of landmine aging for ‘end state’ questions about landmine contamination situations;
- User tools can be improved and expanded to more mine types through the (safe) collection of as much field data as possible;
- Further review of existing literary sources is likely to yield useful input to help refine aging models;
- Refining the VI model to include modifiers like environment and time can yield additional insights in the future
- Further laboratory investigation of the most vulnerable components of mines will help refine aging models.

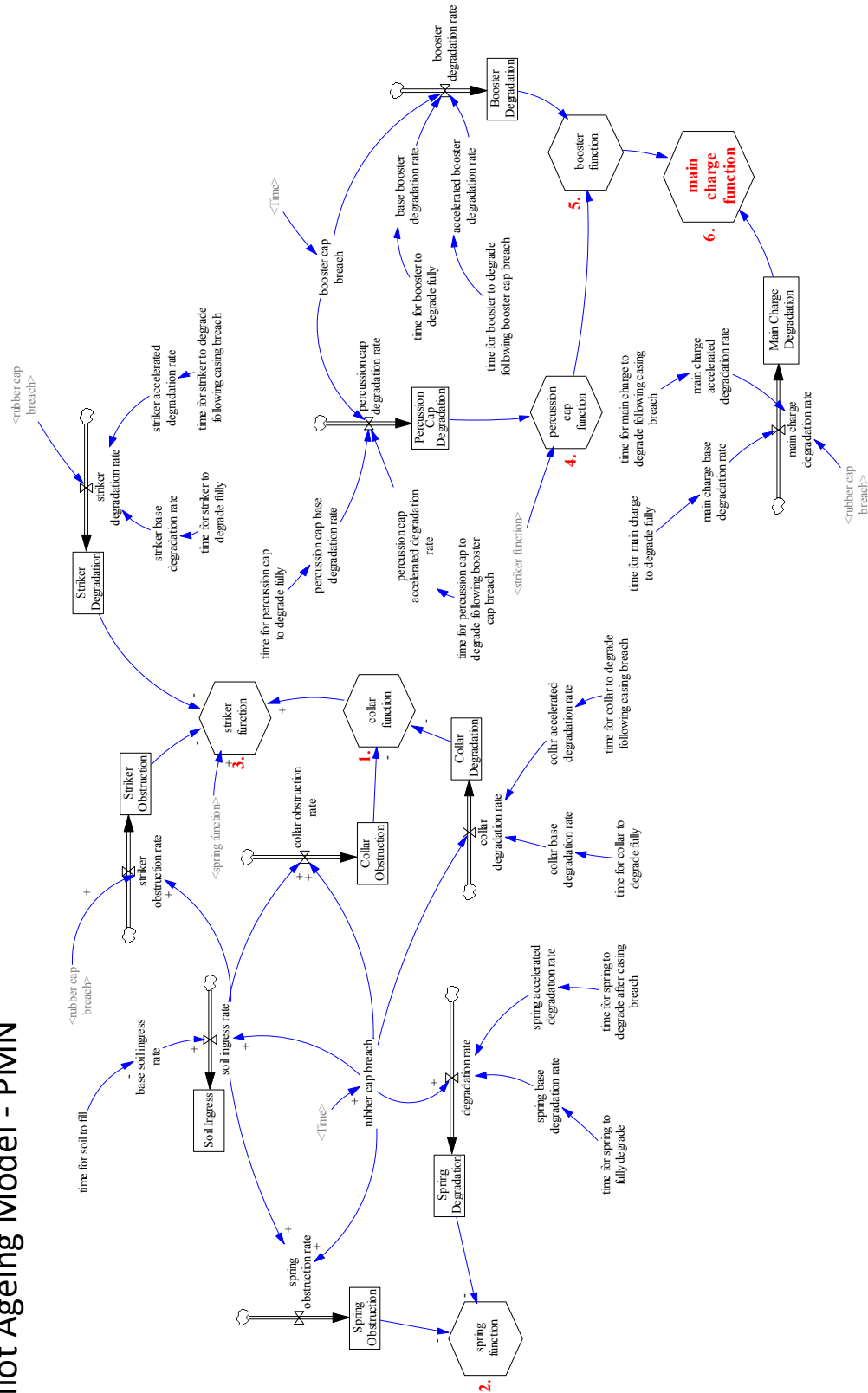
7. Recommendations

It is recommended that:

- **Field data is collected systematically.** Understanding landmine aging at the country level requires extensive statistical analysis. That analysis can only yield reliable results when there is a substantial body of data to work from. It has not been normal practice for clearance operators to collect and report information about the condition of landmines discovered in the field. It is of the utmost importance that such data be collected on a routine basis from now on. An example template for capturing the required data is at *Annex K*.
- **Statisticians become involved in the study.** As field data become available thorough analysis by statistical specialists should be carried out to identify failure patterns and to make projections about the likely lifespan of different mine types in different areas. The reliability of such projections is likely to increase as more data become available and over time.
- **The study is continued.** In particular, further research on dynamic environmental and time impacts on landmine materials will continue to refine our understanding of aging and degradation on landmines. Continued field assessment and sampling will increase our data sets and allow for additional analysis and global understanding of landmine aging.

Appendix 1.

Pilot Ageing Model - PMN



K: Field Information Collection Discussion and Sample Form

A key recommendation of this study is that there should be much greater emphasis on the collection of information about the condition of mines within field programs. It is important to make it clear that there is **no** suggestion that field operators should try to dismantle mines. Normal clearance procedures should be followed reflecting local standards, circumstances, conditions and SOPs.

The study has found that the external condition of a mine often gives a reasonable indication of the likely internal condition. Where there are cracks, holes or other breaches in the mine casing, deterioration of the internal structures and components normally follows relatively quickly. Most mines are cleared through destruction in situ, a process which requires the deminer to locate the object and then positively identify it as a hazardous item (usually with confirmation by a team leader or other superior). To do so, the mine is at least partially exposed for visual inspection. This stage in the clearance process provides an opportunity to assess and record the condition of the mine.

Development of mine lifespan charts depends to a great extent upon the application of statistical techniques, many of them similar to those used by actuaries and others with an interest in how human populations age and die. Like all statistical approaches, the more data there is to work from the better. Today the quantity of data available is minimal, and certainly does not meet the normal criteria necessary to achieve significance. Aging is an increasingly important aspect of mine action and the collection of additional data, to allow statistical analysis to be undertaken justifies the small additional amount of time and effort necessary to collect the data.

It is recommended that the largest possible number of operational organizations and authorities are encouraged to collection information on the condition of the mines that they encounter. Demining organizations will be asked to take a geo-referenced photo and conduct a basic visual inspection of the mine as part of their procedure prior to demolition. It will be made clear that the inspector should not touch the mine or act in any way differently from their normal practice.

At the end of this section is an example of a possible field data collection sheet. It is intended to be quick and simple to complete, placing as little burden upon field operators as possible. A sheet (or sheets) should be completed for each clearance site and submitted with the other normal field operational data. A copy of the sheet, together with the relevant photos, should be provided to CISR as well as to the MAC or other supervisory body.

The key pieces of information necessary to allow analysis are:

- Mine type;
- Depth at which the mine was found;
- External condition of the mine, assessed using a scoring system provided on the data sheet.

The location of the site is provided to allow analysts to assess the general climatic conditions and geology prevailing in the area. The name and organization of the reporter is included to provide traceability in the event that further questions require follow-up.

Sample Field Aging Data Collection Sheet

JMU MAIC Landmine Aging Data Collection Sheet				
Country			Province	
Locality/village			UTM	
Site Reference			Lat/Long	
Reporting Organization			Reporting Individual	
Date	Photo ref	Type	Depth (cm)	Condition Score
10/10/10	001	PMN-2	6	2
Condition	Guidance			Score
Excellent	The mine looks as though it had been laid yesterday; external markings are fully visible, the casing material retains its original color; there is no damage of any sort visible on the exterior of the mine.			1
Good	The mine has suffered some weathering; external markings have faded; colors are no longer clear and uniform; there are no cracks, holes or significant damage to the external materials of the mine.			2
Damaged	The mine is heavily weathered; cracks or breaches are visible in the external materials of the mine.			3
Destroyed	The structure of the mine has broken down; some structures are missing or have rotted away.			4

END