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. 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](image)

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

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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 diagramatic 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)](image)

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 train\(^{59}\) 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

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\(^{59}\) 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. 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.

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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.
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.

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 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 proprieties 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. 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 impact\textsuperscript{62}).
• 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. \textit{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 \textit{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 \textit{disarmed} though aging is highly unlikely to become functional again.

\textsuperscript{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.
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
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:

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

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**

<table>
<thead>
<tr>
<th>RESILIENCE</th>
<th>Materials list</th>
<th>Abbreviation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher</td>
<td>Epoxy composite</td>
<td>EC</td>
<td>6. ‘Resilience’ ranking is based on field observation of deterioration through aging.</td>
</tr>
<tr>
<td></td>
<td>FiberGlass</td>
<td>FG</td>
<td></td>
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<tr>
<td></td>
<td>Bakelite (or thermosetting plastic)</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stainless steel – thick (&gt; 1 mm)</td>
<td>SS+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stainless steel – thin (&lt;1 mm)</td>
<td>SS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>CU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polycarbonate and Acetates</td>
<td>PC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermoplastic - thick (&gt;1 mm)</td>
<td>TP+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermoplastic - thin (&lt;1 mm)</td>
<td>TP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mild steel – plated or thick</td>
<td>MSP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum – thick (&gt; 1 mm)</td>
<td>AL +</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum – thin (&lt;1 mm)</td>
<td>AL</td>
<td></td>
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<td></td>
<td>Mild steel – unplated or thin</td>
<td>MSU</td>
<td></td>
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<tr>
<td></td>
<td>Rubber – thick (&gt; 1 mm)</td>
<td>R+</td>
<td></td>
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<td></td>
<td>Rubber – thin (&lt;1 mm)</td>
<td>R</td>
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<td></td>
<td>Wood</td>
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<td></td>
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<tr>
<td></td>
<td>Cardboard</td>
<td>C</td>
<td></td>
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<tr>
<td>Lower</td>
<td></td>
<td></td>
<td>7. <strong>NA</strong> (not applicable) used where component is absent</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>8. Boosters are not considered because they will be the same as, or higher quality than, main charge rating 1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10. Where striker is absent, use same VI as Firing pin</td>
</tr>
</tbody>
</table>
### Table 2. Component Vulnerability Index

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

### Table 3. Vulnerability of mines by type

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>PMN</th>
<th>PMN-2</th>
<th>PMD-6</th>
<th>M35</th>
<th>M14</th>
<th>M6</th>
<th>M15</th>
<th>M16</th>
<th>M19</th>
<th>MD-82B</th>
<th>P4</th>
<th>SB-33</th>
<th>SB-81</th>
<th>Type 72</th>
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<tbody>
<tr>
<td>Cover</td>
<td>4</td>
<td>4</td>
<td>5</td>
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<td>2</td>
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<td>2</td>
<td>2</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>5</td>
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<td>Casing</td>
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<td>5</td>
<td>3</td>
<td>3</td>
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<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Striker</td>
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<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
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<td>5</td>
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<td>Firing pin</td>
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<td>4</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Striker spring</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
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<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Cap</td>
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<td>3</td>
<td>5</td>
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<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>4</td>
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<td>1</td>
<td>1</td>
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<td>1</td>
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<td>Vulnerability Index (VI)*</td>
<td>19</td>
<td>21</td>
<td>27</td>
<td>16</td>
<td>17</td>
<td>19</td>
<td>19</td>
<td>25</td>
<td>8</td>
<td>24</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>18</td>
</tr>
</tbody>
</table>

*Possible modifiers include environment, soil type and degree of exposure.
Table 4. Mine comparisons

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

![Illustrative mine lifespan chart](image)

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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](image)

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-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 panning. 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

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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:

\[ \text{LMR} = \frac{\text{VI} * \text{E}}{\text{T}} \]  

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 impact\textsuperscript{66}; 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 Jordan\textsuperscript{67} 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:

\textsuperscript{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.

\textsuperscript{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.