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\textsubscript{2}; SiO\textsubscript{2} is found in quartz, which is an important component of sand. The median SiO\textsubscript{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\textsubscript{2}O\textsubscript{3}) and iron (Fe\textsubscript{2}O\textsubscript{3}). The greater proportion of SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3} and Fe\textsubscript{2}O\textsubscript{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.