O-Revealer: Novel technology for demining in peatlands by the controlled use of smouldering combustion

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1 Introduction

After more than thirty years since the 1982 Falklands War, only 5,000 landmines out of the original 20,000 anti-personal (AP) and 5,000 anti-tank (AT) mines placed by the Argentine forces have been demined [1]. Under the *Ottawa Treaty* on Anti-Personnel Mine Ban, the British government had the legal responsibility to remove them by 2009. However, due to the slow pace and expensive use of conventional demining technologies, the government has asked for a 10-year extension [2].

Because a large fraction of the documented 117 minefields in the Falklands are in peatlands [3], this paper studies the feasibility of a novel technology that uses controlled smouldering combustion for locating landmines and other solid objects buried in peat. Peat is an organic soil and known to host current minefields not only in the Falklands but also in Vietnam, Burma, Laos, Uganda, Zimbabwe and the former Yugoslavia. This technology, called O-Revealer, was first proposed in 2007 to the UK Ministry of Defense [4] and based on smouldering combustion, which is the slow, low-temperature, flameless burning of porous fuels [5]. Despite the existence of a body of literature on the ignition and spread of smouldering fires in peatlands (*e.g.* [6-8]), it has never been used before for demining.

Smouldering fires can ignite and spread in soils up to a maximum moisture content (MC) of 100-200% [7, 8], and continuously burn for weeks or even months [6]. Therefore, once smouldering fires are initiated in a minefield, especially in the dry seasons, they may consume the surface soil layer, and expose mines (easy detection) to be safely removed afterwards. For the smouldering combustion of high-organic soils like peat, the heat of combustion is 8-18 MJ/kg in the dry basis [9], and the typical peak temperature is around 500 °C. The spread rate of smouldering fire in peat is on the order of cm/h, leaving a sufficient long residence time in a high temperature (*e.g.* 300°C for 1 h) to sterilize soil [8]. For the same reason, this strong thermal impact may also be able to melt (or even burn) plastic mines, and to thermally trigger a mine explosion.

O-Revealer will consist of a set of techniques to thoroughly control the fire by combining external ignition, forced ventilation, site compartmentation, and suppression. It would also take into account the local weather conditions, and by mastering the process of smouldering acting on the spread of the fire front, we envision an inexpensive, reliable, easy-to-deploy, efficient and safe technology that excels at the most important issues of humanitarian demining including detection of non-metallic mines, avoiding false negatives, and reaching high demining rates.

O-Revealer poses two important issues that are addressed in this paper: mitigate the environmental impact on the soil ecosystem, and avoid thermal triggering of the explosives. It is foreseen that O-Revealer will be best applied under certain seasons of the year (dry season in tropical regions and warm season in boreal regions). It is necessary to study the effect of soil type and the atmospheric conditions that best allow for controlled smouldering and mitigate the environmental impact on the soil ecosystem. This has never been investigated before for smouldering combustion although some knowledge exists for flaming combustion for prescribed fires. The mines can be thermally triggered

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either through the primary (detonation at 350 °C) or the secondary explosives (thermal runaway at 240 °C). Therefore, the lower trigger temperature of the secondary explosive serves as the benchmark in the experiments to determine the risk of mine explosion.

In this work, we report on the very first laboratory experiment designed to study the thermal impact of smouldering peat fire on two different landmines, one plastic and one metallic. The thermally equivalent mine dummies were produced and tested under different soil MCs ranging between 5% and 130%. The temperature distributions in peat and dummies are measured to study the thermal characteristics of the fire, damage to the mines, and the risk of a thermal triggering for the explosive.

2 Experimental methods

As a case study, two types of landmines, (i) Italian SB-33 anti-personnel plastic landmine, and (ii) Serbian PROM-1 anti-tank metallic landmine, were selected and two corresponding dummies were built for the experiments (Fig. 1). The SB-33 mine is widely present in Falkland Islands, and is mostly made of polycarbonate (PC) with a minimum metal content plus 35 g of research department explosive (RDX) [10]. Figure 1a shows the detailed structure of our SB-33 mine dummy, 3D printed in PC to the real dimensions with a height of 30 mm and a diameter of 85 mm. The majority of current landmines are made of metal, and the Serbian PROM-1 is one of the most representatives. It is made of steel, has a bottle shape (Fig. 1b), and includes 439 g of explosive [10]. In our experiment, a steel cylinder with inner diameter of 71 mm, height of 140 mm, and wall thickness of 4 mm was used. Commercial chalk powder was found to have the same thermal diffusivity as RDX, and therefore was placed inside the mines at the explosive location to simulate its heat transfer behaviour in a safe manner.

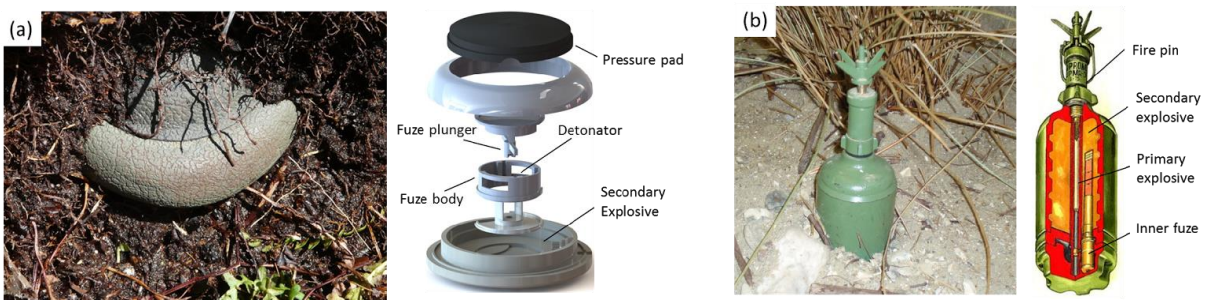

Figure 1. Photo in minefield and structure illustration of (a) an Italian SB-33 plastic min (https://www.flickr.com/photos/73614187@N03/7000453084/); (b) a Serbian PROM-1 metal mine (http://www.cat-uxo.com/#/prom-1/4566561813).

We use a commercial Irish moss peat soil as the testing soil because it is homogenous and has repeatable composition (Fig. 2). It has a high organic content of 98% and a dry bulk density of 140 kg/m^3. In order to obtain a desired MC, the peat was first dried at 100 °C for 48 h, and then well mixed with the corresponding amount of water and let to rest for another 48 h for homogenization. The MC values for very dry (5%, in equilibrium with laboratory air moisture), dry (50%), and normal (100% and 130%) peat conditions were targeted. Wetter conditions would not support the spread of smouldering for this peat type. A fire box with an inner dimension of 20×20×10 cm and a 1.27 cm insulation wall was used to safely confine the smouldering fire (similar to the design in [8]). The fire was ignited by a 20 cm coil heater (attached to one side wall and 5 cm below the surface) with a heating power of 100 W for 30 min.

The SB-33 dummy was placed above a 5-cm layer of peat, and covered by a 2-cm layer on the top, as shown in Fig. 2a and b. Three thermocouples (TCs) were inserted through the bottom of box into the mine, and positioned in the fuse assembly, detonator, and secondary explosive, respectively. For the PROM-1 dummy, the bottom 10 cm of the mine body was covered by peat to recreate how this

mine is buried in real minefields, with its neck pointing upwards out of the soil (Fig. 1b). Five TCs from the top were inserted into the chamber of secondary explosive under different depth (Fig. 2c). For both mines, additional TCs were placed in the peat around the mine. These TCs scanned every 5 s to monitor the temperature evolution.

Figure 2. Photos of the laboratory experimental setup before ignition: (a) fire box with the SB-33dummy; (b) SB-33 dummy completely covered with peat layers; (c) PROM-1 dummy buried in peat.

3 Results and discussions

Once ignited, the smouldering front would spread both horizontally and in-depth up to a maximum MC of 130%. Without mine, TC measurements showed that the horizontal fire spread rate was around 1 mm/min for very dry soil at 5% MC, and 0.5 mm/min at 100% MC. The in-depth spread rate was slower, on the order of 0.1 mm/min, and decreases with the depth and MC. After the fire, the original peat soil will be completely consumed. The residue was only 3% of the original mass of peat and made mainly a shallow layer of white ash plus a small amount of char.

3.1 Results for SB-33 dummy

Figure 3 shows the fire spread over the peat where the SB-33 dummy is buried. The dummy was damaged by heat and completely revealed to the open. The bottom shell had melted and pyrolyzed, leaving some chalk powder mixed with ash from the soil. However, the inner fuse assembly showed little damage (Fig. 3c).

Figure 3. Test with SB-33 dummy in peat with a moisture content of 50%, (a) during smouldering fire spread; (b) after burn out; (c) residue of dummy.

Figure 4a shows the temperature measurements in the 50% MC peat, including the melting temperature of PC, 155 °C [11], as reference. During the 30 min of coil heating, the peat near the coil was heated up to 500 °C, resulting in a successful ignition, while the temperature near and inside the mine increased by less than 30 ˚C during ignition. The peak temperature in the peat during fire spread ranged from 450 to 570 °C, and very little residue was left behind the front, similar to the case without

the mine. The smouldering fire showed to sustain a temperature higher than the PC melt point for up to 4 h, justifying the observation of melting damage to the bottom shell (Fig. 3c). Figure 4b shows the temperature evolution inside the dummy, and includes the minimum thermal runaway temperature of RDX (240 °C [12]) as reference. Note that the runaway temperature for RDX can be as low as 185 °C with impurity, and can be accelerated once reaching its melt point (below 200 °C). It was found that the RDX could reach this thermal runaway temperature for about 30 min. These thermal conditions for the dry peat at 50% MC are not severe but could trigger the explosive.

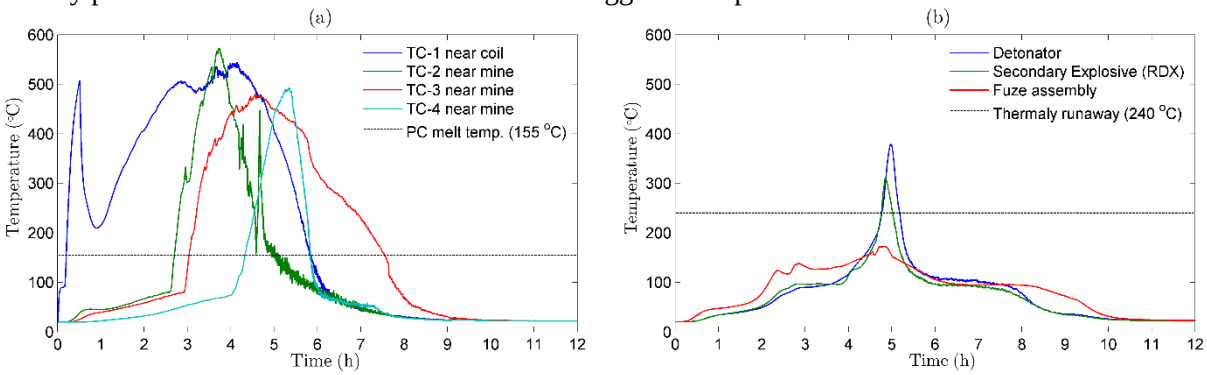

Figure 4. Thermocouple measurements in the SB-33 dummy and in the peat with moisture content of 50%, (a) inside the peat around the dummy, and (b) inside the dummy.

Figure 5a shows the TC measurements with peat at 100% MC. The peak temperature was found to be similar to the case of 50% MC, around 500 °C. However, in some peat locations near the mine, it did not reach the PC melting point for more than 10 min. For the temperature inside the dummy, the thermal runaway temperature of RDX was not reached for this peat at normal MC conditions. Note that multiple small peaks in temperature measurement came from the overhang of peat, *i.e.* smouldering peat tends to spread in a depth below the top surface. The unburnt overhang was not stable and collapsed once a while to cover the thermocouple below, which would also burn to create several small temperature peaks. And the small temperature oscillation came from the emission gas temperature measurement when thermocouples detached from the solid phase.

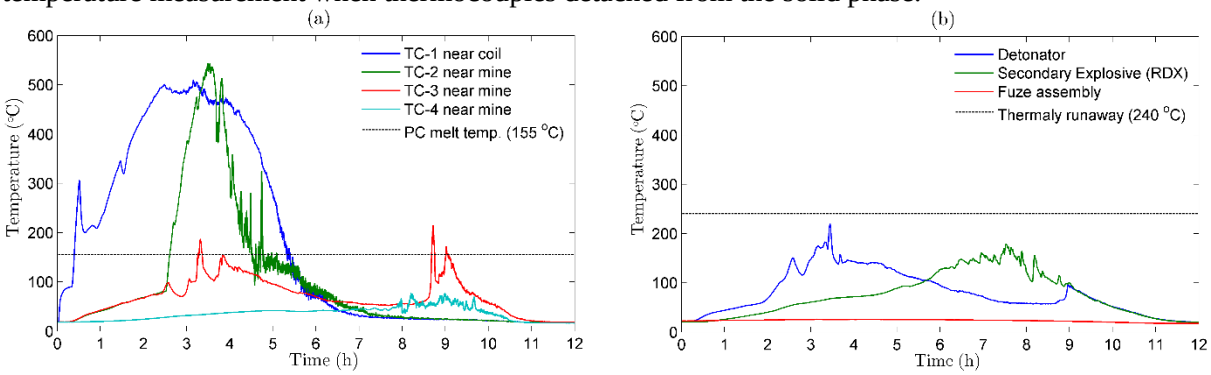

Figure 5. Thermocouple measurements in the SB-33 dummy and in the peat with moisture content of 100%, (a) inside the peat around the dummy, and (b) inside the dummy.

3.3 Results for PROM-1 dummy

At least two repeats were conducted for each MC value, and the temperature measurements showed a good repeatability (±10 ˚C on average). Figure 5 shows the fire spread for the PROM-1 dummy buried 50% MC peat. In addition to the 5 TCs placed inside the dummy, another 8 TCs were placed outside: 5 cm below the peat surface along the central axis of horizontal fire spread. Figure 5 shows the process of fire spread over the PROM-1 dummy. Once ignited, only ash and char residue of 3 to 4% of the original peat mass were left after burn out. The dummy was left physically undamaged and was completely revealed to the open (Fig. 5c).

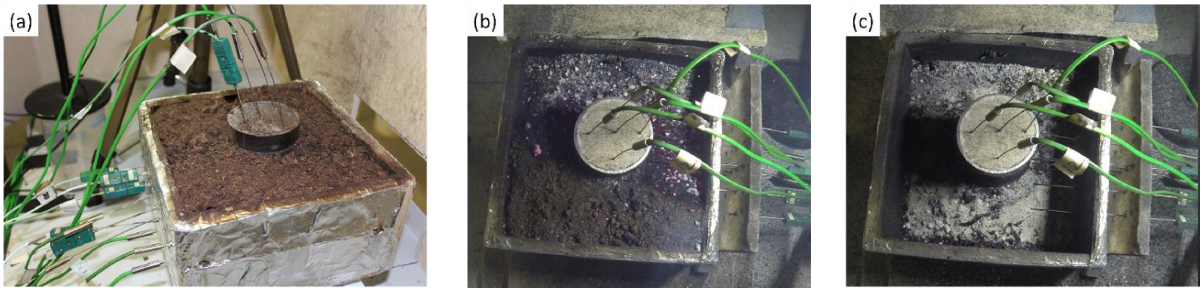

Figure 5. Test of PROM-1 dummy in peat with moisture content of 50%, (a) before ignition; (b) during fire spread; (c) after burn out.

Figure 6 shows a group of TC measurements both outside and inside the dummy for 5% MC (very dry peat). The peak temperature in the peak is around 550°C, similar to the case without dummy and with the SB-33 dummy (Fig. 4a). For the TC near the PROM-1 dummy, the peak temperature is much lower by 100°C, arguably due to cooling heat transfer by the steel. The temperature inside the dummy shows a good uniformity across different locations arguably because of the high thermal diffusivity of steel and the thin shell. The peak temperature inside the dummy was found to be 200°C, below the minimum thermal runaway temperature of RDX.

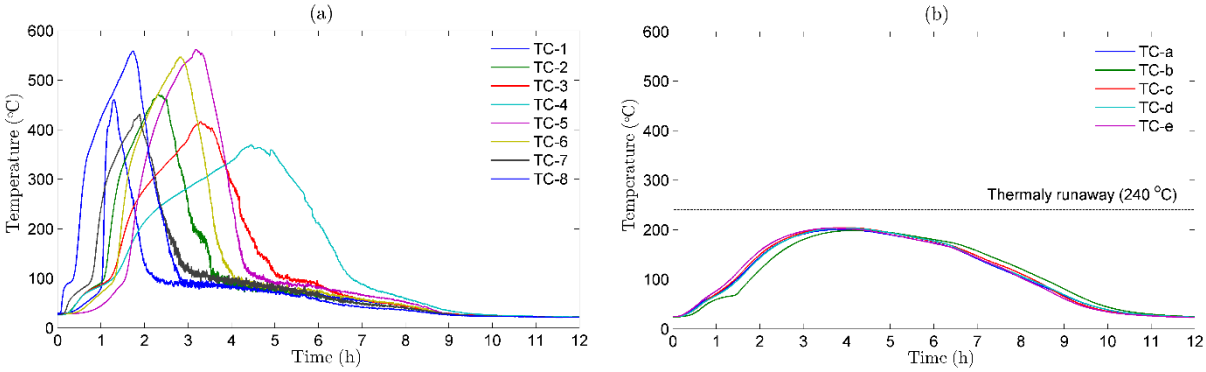

Figure 6. Thermocouple measurements with the dummy model of PROM-1 metal mine and dried soil moisture content of 5%, (a) 5 cm below the soil surface outside the mine, and (b) inside the mine.

Figure 7 shows TC measurements inside the dummy for 50% and 100% MC. The peak temperature decreases with increasing soil moisture: 170°C at 50% MC and 105°C at 100% MC, implying an even lower possibility for the thermal runway of RDX.

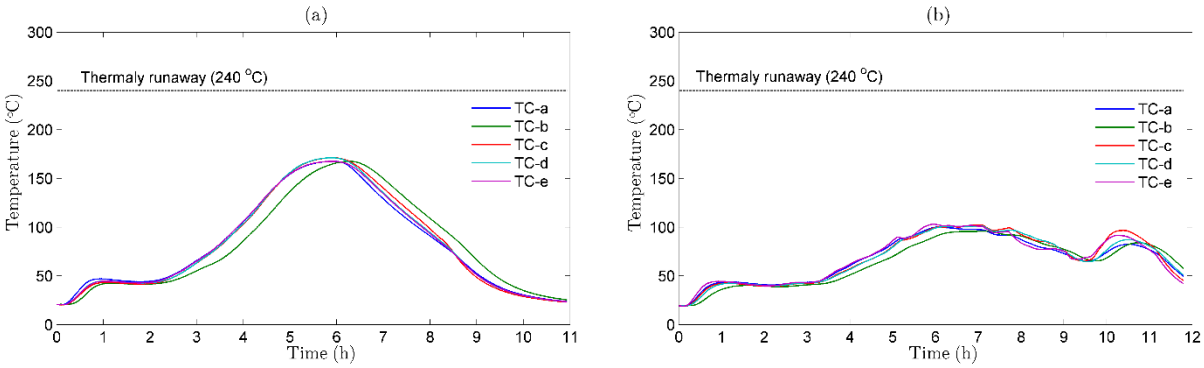

Figure 7. Thermocouple measurements inside the PROM-1 dummy for, (a) MC = 50%, and (b) MC = 100%.

4 Conclusions

In this work, a novel technology was proposed to detect various types of landmines buried in peat using the controlled smouldering combustion. Two types of mines, Italian SB-33 anti-personnel plastic landmine, and Serbian PROM-1 anti-tank metal landmine were selected. Their corresponding dummies were built and buried in peat with the MC ranging from very dry (5%) to normal (130%) conditions. In all cases, the smouldering fire burns across the peat, left the dummy exposed to the open for easy identification and removal. As the peat MC increased, the temperatures inside and outside of the dummy and the fire spread rate decreased. For the SB-33 dummy, the results showed that the fire was strong enough to melt the polycarbonate shell, and to heat the explosive charge above the minimum thermal-runaway temperature (240°C) for 30 min for dry peat at 50% MC. For a wetter peat at 100% MC or above, the dummy did not reach the threshold of thermal runaway. For the PROM-1 dummy, the results showed that the peak temperature inside only reached 205°C for the very dry peat at 5% MC, well below the thermal runaway temperature.

This study proves the concept of the novel technology in small-scale laboratory conditions. We envision that O-Revealer will be applied in small plots of land, one at a time by each team, and following a strategy of combining it with other demining methods. Although not all organic lands or weather conditions will be apt to this technology, we have identified the Falkland Islands as the first site of immediate interest for this technology, and it can be further applied in many more minefields around the world.

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