Neutralisation of Landmines Using a High-Power Microwave Applicator

Phase 1 Field Trial Results and Analysis

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Abstract

In 1995, the [then] Defence Research and Development Branch (DRDB) initiated a project to investigate the feasibility of using High Power Microwaves (HPM) to destroy landmines buried in soil. The technique assumed that the location of a landmine could be pin-pointed using a complementary detection method. The HPM concept envisaged consists of a microwave emitter located at some distance from the landmine. Irradiation of the area directly above the suspected landmine location would result in bulk heating of the soil and landmine components until physical damage or ignition of the landmine materials would occur, thereby resulting in destruction of the latter.

This report is concerned with some of the early experiments that were performed in 1997 under the HPM project. A first series of experiments, which were carried out at the Defence Research Establishment Ottawa, demonstrated that mine-like targets constructed from various plastic materials could be heated to the point of melting, and in some cases, to temperatures sufficient to initiate combustion. Based on the results of these first tests, a second series of experiments were carried out at the Defence Research Establishment Suffield against actual landmine components and fully assembled landmines. The results of both series of tests are reported herein.

Résumé

En 1995, la Direction pour la Recherche et le Développement pour la Défense (DRDD) commençait une enquête pour déterminer la faisabilité d’utiliser les Micro-ondes de Haute Puissance (MHP) pour détruire des mines terrestres enfouies dans le sol. La technique proposée suppose que l’emplacement de la mine est déjà connu grâce à un système de détection indépendant. Le concept MHP consiste en un émetteur situé à une certaine distance de l’engin explosif. En irradiant la surface au-dessus de la mine, le sol est réchauffé en masse à une telle température que les composantes de la mine fondent ou qu’il y ait allumage des matériaux composant la mines. Ce processus résulte en la destruction de la mine.

Ce rapport décrit les résultats de deux séries d’expériences qui furent complétées en 1997 sous la tutelle du projet MHP. Une première séries d’essais, qui eurent lieu au Centre de recherches pour la défense Ottawa, démontrait que des cibles construites de matériaux plastiques pouvaient être chauffées au point de fondre, et dans certain cas, jusqu'au point de combustion. À la suite des résultats obtenus lors de ces premiers essais, une seconde série d’essais furent fait au Centre de recherches pour la défense Suffield contre des composantes de mines terrestres ou contre des mines complètes. Les résultats de ces deux séries d’essais sont rapportés dans ce rapport.

Executive summary

In late 1993, the Chief of Defence Staff directed the Defence R&D Branch (DRDB) to develop an improved landmine detection system for the Canadian Forces. Following a 1994 scoping study of countermine technology, the DRDB made a number of recommendations that paved the way to the development of the Improved Landmine Detection System (ILDS), which focussed on landmine detection for route clearance. The neutralisation aspect of landmines was deferred to a separate project.

In 1995, the Defence Research Establishment (DRE) Suffield initiated a mine neutralisation study to determine what technologies could be used in concert with the ILDS. The study recommended several options to meet the needs of the Canadian Forces. For the short term, a mini-flail could be used in concert with an array of shaped charges. There was a need to establish the effectiveness of these methods for a range of operational conditions. For the long term, the study recommended to investigate the potential of heterogeneous in-soil explosives and High Power Microwaves (HPM).

In 1995, research groups from the DRE Suffield and Ottawa combined their expertise and efforts to investigate how HPM technology could be applied to the landmine neutralisation problem. The HPM concept proposed for point neutralisation of buried landmines consists of a microwave antenna placed 5-7 meters away from the target landmine. The antenna would focus a microwave beam on the soil above the mine to heat up the soil to the point of initiating combustion within the landmine.

Early during the HPM project, it was demonstrated that the technology could sufficiently heat a soil medium and that thermal heating of a buried landmine was possible. Based on these results, it was decided to assemble a breadboard system to demonstrate the HPM concept against a variety of surrogates and actual landmines. The experiments against plastic landmine surrogates showed these could be heated to well above their deformation temperature within a few minutes. Many of the surrogates were in a gelatinous state when removed from the soil and could easily be crushed with a gloved hand, thereby indicating that significant deformation of the case of a plastic landmine could be expected. It was also reasonable to expect that the explosive content of a real landmine would heat in a similar fashion. The initiator and booster materials in the fuse would be particularly susceptible to such heating.

Based on the positive results against landmine surrogates, it was decided to proceed with subjecting actual components from PMA-1, PMA-2 and PMA-3 landmines to HPM heating. These landmines offered targets of very different shapes and configurations. The experiments were performed on individual fuses and mine bodies in order to isolate the effects of microwaves on these components.

The tests against fuses in isolation demonstrated that fuse construction and orientation had a strong effect on the results. For example, the UPMAH-1 fuse could be defeated within a few seconds when its long axis was aligned with the electric field. When the same fuse was rotated by 90^{o}, it could not be defeated. Initiation of the UPMAH-2 fuse was achieved in just over 1 minute and that of the UPMAH-3 fuse in a little more than 5 minutes.

Tests against the PMA-1 and PMA-2 landmine bodies resulted in the melting and burning of the case and its explosive content with a few minutes of heating. A similar result was obtained against fused and armed landmines, which effectively resulted in the neutralisation of these

landmines. In two of the tests, high order detonation of a PMA-1 and a PMA-2 landmine was achieved.

Opportunity tests against the electronic fuse of a modern anti-tank landmine, the FFV-028, did not yield any conclusive results. Inspection of the electronic fuse functionality before and after the test did not reveal any permanent damage. It should be noted that the functionality of the electronic fuse during irradiation was not monitored.

It appears from the results of these experiments that it is feasible to neutralise buried landmines using HPM technology. There is however a need to continue the investigation of this technology to determine if HPM neutralisation is operationally practical and cost effective. It is recommended that the following course of action be taken:

- Design and construct a standoff antenna to apply microwave energy from a distance and improve the survivability of the applicator while reducing risk to personnel; and
- Study the coupling of microwave energy to fuse components to pinpoint the mechanisms at work in defeating buried landmines and to assess the influence of fuse orientation.

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Sommaire

Vers la fin de 1993, le chef de la défense nationale ordonnait à la Direction de la recherche et le développement pour la défense (DRDD) de développer un meilleur système de détection de mines terrestres pour les Forces canadiennes. Suite à une revue des technologies de contre-minage en 1994, la DRDD faisait plusieurs recommandations qui résulta au programme de développement du *Improved Landmine Detection System* (ILDS), système qui était conçu spécialement pour la détection sur les routes. L'aspect de neutralisation des mines détectées était rapporté à un autre projet.

En 1995, le Centre pour la recherche et développement pour la défense (CRD) Suffield lançait une étude des technologies de neutralisation des mines terrestres qui pourraient être utilisées avec ILDS. Plusieurs options étaient recommandées aux Forces canadiennes. A court terme, un mini-fléau et un ensemble de charges creuses pouvaient être utilises, en autant que l'efficacité de ces technologies serait établie sous des conditions opérationnelles. A plus long terme, l'étude recommandait d'évaluer le potentiel des explosifs liquides distribués en sol ainsi que les Micro-Ondes de Haute Puissance (MHP).

Suite à cette étude, des groupes de recherche des CRD Suffield et Ottawa combinaient leurs expertises pour déterminer comment la technologie MHP pourrait être appliquée au problème de neutralisation des mines terrestres. Le concept MHP proposé pour la neutralisation ciblée des mines utiliserait une antenne placée entre 5 et 7 mètres de la mine. Cette antenne servirait à concentrer des micro-ondes immédiatement au-dessus de la mine afin de chauffer le sol à une telle température que la mine commencerait à brûler.

Tôt durant le projet MHP, il a été démontré que cette technologie pouvait chauffer le sol à de hautes températures et que le transfert de chaleur à des mines enfouies était possible. Suivant ces résultats encourageants, il a été décidé d'assembler un banc d'essais pour évaluer le concept MHP contre différentes mines factices et réelles. Les expériences contre des mines factices construites en plastique ont prouvé qu'en quelques minutes, ces dernières pouvaient être chauffées bien au-delà de la température nécessaire pour les faire fondre. Plusieurs des mines factices étaient en un état gélatineux lorsqu'elles ont été retirées du sol et pouvaient être écrasées à la main, indiquant donc que la même processus affecterait le caisson en plastique de véritables mines terrestres. Il était aussi raisonnable de spéculer que l'explosif contenu dans ces mêmes mines serait aussi chauffé. Les matériaux contenus dans l'amorce seraient tout particulièrement susceptibles au transfert de chaleur.

Étant donné les résultats obtenus contre les mines factices, la décision fut prise de procéder à la prochaine étape et de soumettre de vraies mines terrestres à l'échauffement par MHP. Les mines PMA-1, PMA-2 et PMA-3 offraient des cibles de formes et configurations variées. Certaines des expériences furent faites contres les amorces ou contre la charge principale en isolation afin de déterminer l'effet de MHP contre ces composantes.

Les essais contre les amorces ont démontré que la construction et l'orientation de ces dernières étaient des facteurs importants. Par exemple, l'amorce UPMAH-1 était neutralisée en quelques secondes lorsque son axe principal était aligné avec le champ électrique. Quand la même amorce était à 90º par rapport au champ électrique, il était impossible de la neutraliser. Les amorces UPMAH-2 et UPMAH-3 ont été chauffées au point d'allumage en à peu près 1 minute et 5 minutes, respectivement.

Les essais contre les charges principales des mines PMA-1 et PMA-2 ont mené à la fonte et l'allumage de ces derniers en dedans de quelques minutes d'échauffement. L'effet était á peu près le même contre des mines complètes, ce qui résulta effectivement à la neutralisation de celles-ci. Pour deux des essais, contre une PMA-1 et une PMA-2 respectivement, il y eut détonation de la mine.

Deux essais ont aussi été faits contre l'amorce électronique d'une mine anti-char moderne, la FFV-028, mais ces derniers n'ont pas mené à des résultats conclusifs. Une inspection des amorces avant et après les essais a révélé qu'aucun dommage permanent n'avait été infligé. Il est important de noter que la fonctionnalité de l'amorce pendant l'essai n'a pas été mesurée.

Les résultats de ces essais indiquent qu'il est possible de neutraliser des mines terrestres enfouies en utilisant la technologie MHP. Il y a cependant un besoin de d'élargir les recherches du projet afin de déterminer si un système MHP peut être pratique pour déploiement opérationnel et de bonne valeur monétaire. Il est donc recommandé de poursuivre le projet de la façon suivante :

Concevoir et construire un démonstrateur technologique avec antenne pour concentrer l'énergie MHP à distance afin d'étudier la survie de l'antenne aux effets de souffle tout en réduisant les risques au personnel; et

Étudier le couplage entre les micro-ondes et les composantes des amorces de mines afin d'établir les mécanismes qui contribuent à la neutralisation de mines enfouies ainsi que la dépendance de l'efficacité du couplage micro-ondes avec l'orientation de l'amorce.

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Acknowledgements

For a project to be successful, it requires contributions from many individuals. This is what makes or breaks the project. Unfortunately, only a few names appear on a report and, too often, essential contributions from individuals working in the background are forgotten soon after the project is over. Here, the authors would like to list the personnel that contributed to this project, from start to finish, both to thank these people, but also to stress the importance of a team effort to achieve the successful outcome of a project. We are indebted to (not in any particular order):

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1. Introduction

During the early 1990's, Canadian Forces soldiers deployed abroad suffered a large number of landmine accidents [1]. Many of these accidents involved vehicles that were struck by low metal content landmines buried in roads. The existing detection technology, which was primarily based on metal detection, had failed to detect those landmines in the path of vehicles. In late 1993, the Chief of Defence Staff directed the Defence R&D Branch (DRDB) to address this problem. By the spring of 1994, following a scoping study of countermine technology [2], DRDB made a number of recommendations that paved the way to the development of the Improved Landmine Detection Project (ILDP). ILDP was immediately transitioned to the major acquisition project L2684, Improved Landmine Detection System (ILDS). From its onset, the ILDP/ILDS projects focussed on the detection aspects of route clearance. The neutralisation aspect of landmines was deferred to a separate project.

Building on the Countermine R&D Study, the Defence Research Establishment (DRE) Suffield initiated a mine neutralisation study [3] in 1995. The scope of this study assumed that the neutralisation activities would follow a robotic detection vehicle from ILDS. The study recommended the pursuit of several options to meet the needs of the Canadian Forces. For the short term, a mini-flail could be used in concert with an array of shaped charges. There was a need to establish the effectiveness of these methods for a range of operational conditions. For the long term, the study also recommended to investigate the potential of two more technologies: heterogeneous in-soil explosives and High Power Microwaves (HPM). The present report is concerned with the latter technology.

While DRE Suffield worked extensively with countermine technologies and was familiar with the landmine portion of the work, HPM technology applications were being researched at DRE Ottawa. Thus, research groups from both laboratories combined their efforts for this project, which was initiated in 1995. The end-state HPM concept proposed for the point neutralisation of landmines is depicted in Figure 1. It consists of a microwave antenna that is mounted on an armoured vehicle and placed 5-7 meters away from the target landmine. The antenna would focus a microwave beam on the soil above the mine to illuminate the area with 10's of kW of power. The soil would heat up to the point of initiating combustion within the landmine. Alternatively, intense microwaves could cause arcing around metallic components in the landmine and cause it to function or burn.

To investigate the feasibility of this concept, a series of trials was organised [4] to prove that HPM could sufficiently heat a soil medium. The experiments involved measuring the heating rates of soil exposed to microwave power. It was shown that the heating rate depends on the amount of power being 'pumped' into the soil. The HPM effectively produces bulk (volumetric) heating of the soil, but beam dispersion and losses in the medium result in greater heating near the surface. The soil moisture content effectively determines the absorption properties of the soil. With very dry soil the microwave energy can penetrate meters below the surface, but under normal moisture conditions penetration depths of 5-10 cm are typical. It should be noted that this is an *instantaneous* effect, unlike conventional surface heating methods. As the soil is exposed to microwave energy, the temperature increases rapidly until it reaches a plateau at 100°C while moisture is vaporised. Once the soil has been depleted of its water content, temperature continues to rise and the microwave penetration depth ***increases***. This study therefore concluded that thermal heating of a landmine was possible. Encouraged by the DRE Ottawa results, it was decided to assemble a breadboard system to demonstrate the HPM concept against a variety of surrogates and actual landmines. The latter experiments were performed at DRE Suffield during the spring of 1997 and involved personnel from both laboratories.

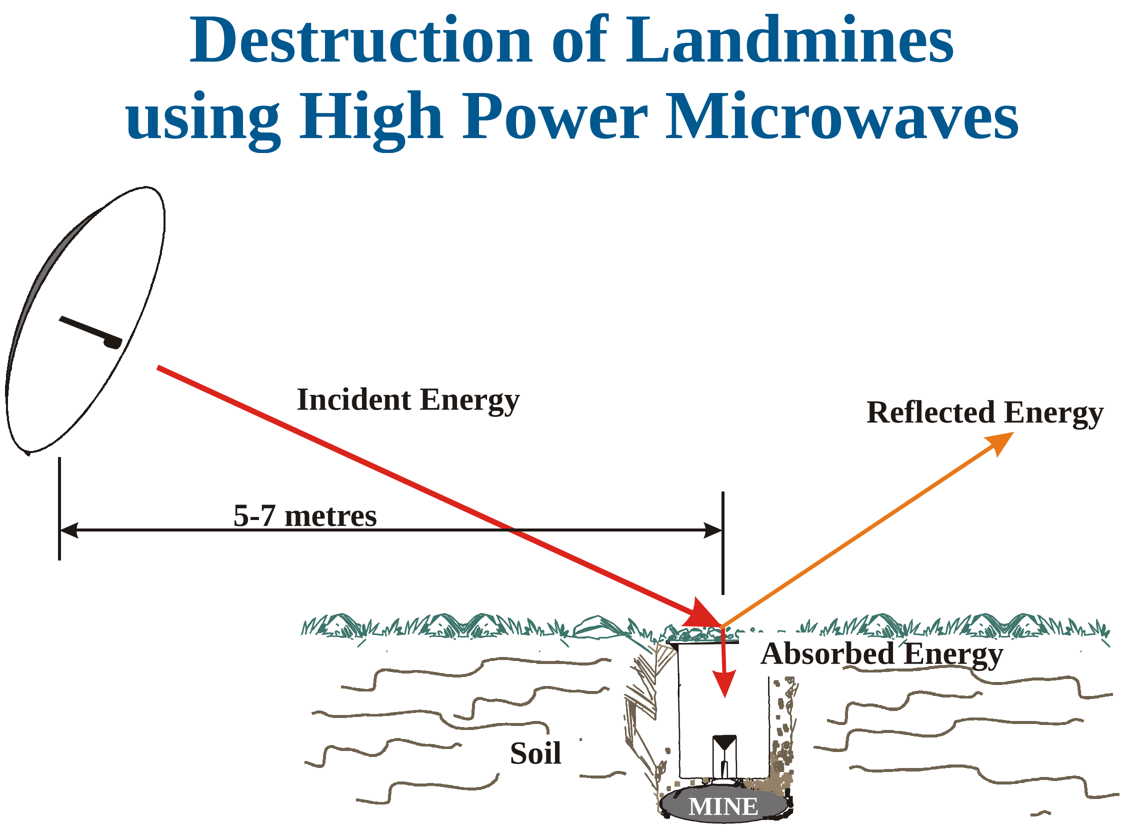

Figure 1. *Concept for a landmine neutralisation system using HPM.*

1.1 Previous Landmine Neutralisation Studies using HPM

A search of the open literature about neutralisation of landmines using HPM, complete with experimental data, yielded few results. Two studies were nevertheless obtained. The first study by Graham [5] looked into the feasibility of a focussed microwave array for detecting and neutralising buried landmines. A focussed array consists of a series of flat elements with precision-machined slots from which microwave radiation occurs. The neutralisation concept was based on the ability of the system to concentrate sufficient microwave energy on a small patch of ground approximately 25-30 cm^2 in size to reach a field intensity over 100 W/cm^2. Neutralisation of the landmine is obtained through melting the plastic components of the pressure plate in order to disable the functioning mechanism. Furthermore, the author was trying to avoid the initiation of a high order detonation of the landmine.

Graham describes proposed experiments against inert M19 landmines. The M19 is an anti-tank device constructed mostly with plastic and rubber materials. It has a large pressure plate that is raised above the top surface of the case. The intent was to subject inert targets to intense heating within a microwave oven to bind the plate with the case as to prevent proper initiation of this landmine. The results of these proposed experiments were not obtained.

The results from a study by Bird and Czigledy [6] were reported. The landmines selected were the M14, VS-50 and PMN landmines. The first two types are constructed from plastics and rubber while the last type is constructed from bakelite and rubber. Further technical details about these landmines may be obtained from several references (e.g. [7]). The work by Bird and Czigledy was methodical, starting with a detailed laboratory analysis of the dielectric properties of materials obtained from the actual landmines. These properties were determined for a wide range of microwave frequencies. They established that many of the plastic and rubber materials used in the construction of these anti-personnel (AP) landmines are susceptible to heating from microwaves. With sufficient power, these materials can be heated to the point of being deformed and even to the point of ignition. A similar analysis of several explosives contained in landmine revealed that the secondary explosives, which make up the main charge of landmines, are not susceptible to microwave heating. A similar conclusion was reached for most of the primary explosives contained within detonators and was proven through experiments.

Bird and Czigledy measured the thermal response of inert M14 and VS-50 landmines placed in microwave ovens operating at the commercial 2.45 GHz frequency. Data was obtained for open-air conditions as well as with the landmines buried in dry and wet soil. The results showed that the presence of water in the soil slows down the heating of the landmine as the water preferentially absorbs the microwave energy. The report also suggests that this particular response is tied to the frequency used in these particular experiments. Changes to the phenomenology are expected for other frequencies.

Other experiments at 2.45 GHz by Bird and Czigledy involved inert and operational M14 landmine components with and without their explosive content. A test with an inert M14 with an operational detonator resulted in a detonation. It was determined that that detonation was initiated from cook-off due to heat build-up as the plastic components of the mine case were melting. When an operational M14 without a detonator was exposed the microwaves, it resulted in burning of the case and its content without a high order detonation. The same experiment with detonator led to detonation with complete destruction of the oven.

1.2 Organisation of this report

The present report is organised to present the results from two separate, but complementary series of tests. It also provides additional background information about the theory of microwave heating of soil and other components often found in landmines. Hence, this report is organised as follows:

- Section 2 gives the background theory for microwave irradiation. The section is divided according to the general classes of materials that make up a landmine, i.e., plastics, explosives and metals. The properties of soil are also considered given their importance to this problem.
- Section 3 describes the experimental details and presents the results obtained for a series of tests carried out at DRE Ottawa with mine-like surrogates. The study concentrated on the thermal response broad classes of materials such as plastics, rubbers and Bakelite.

- Section 4 describes the experimental details and presents the results obtained for a series of tests carried out at the DRE Suffield with AP landmine components and fully functional landmines. In addition, given the opportunity of using actual landmines, exploratory experiments were performed to determine the feasibility of using microwave heating and a infra-red camera to detect buried landmines.
- Section 5 presents the conclusions and recommendations from this work. It should be noted that the present report is only one of several that describe the many aspects of this project.
- Annex A provides a compilation of the data gathered from the tests. It includes a reproduction of the test reports generated by the DRE Suffield Field Trial Officers along with pictures that describe some of the experimental results obtained.

2. Background Theory

2.1 Dielectric Properties of Plastics

When dealing with moist materials such as soil, the dominant loss mechanism is dipole heating due to the presence of water. On the other hand, there is virtually no water in a non-conducting insulator [8] such as nylon or other synthetic substances. In addition, the Maxwell-Wagner type effects [9] play no part in the heating process for a homogeneous material with few impurities. Hence, the only heating mechanism is a result of the dipolar nature of the material itself and, in general, plastics heat at a much slower rate than the surrounding soil. The heating rate in plastics can be related to the dielectric constant by

$$\Delta T = P \Delta t / (m c_p) \tag{1}$$

$$P = \omega \varepsilon'' E^2 \tag{2}$$

where ΔT is the temperature change, P is the absorbed power, Δt is the exposure time, m is the mass of the sample, c_p is the specific heat of the sample and E is the electric field. The process is assumed to be adiabatic. ε'' is the loss term associated with the dielectric constant

$$\varepsilon = \varepsilon' + \mathrm{i}\ \varepsilon'' \tag{3}$$

where ε' is the relative dielectric constant. The effective conductivity of the material is by

$$\sigma = 2\pi f \varepsilon'' = \omega \varepsilon'' \tag{4}$$

where f is the frequency. Values of ε', ε'', c_p and density (ρ) for various materials relevant to mine neutralisation are tabulated in Table 1 for reference. The values for water, dry sand and moist sand (3.88% moisture) are also included for comparison. A typical heating rate can be calculated by substituting eq. (1) into eq. (2)

$$\Delta T = \omega \varepsilon'' E^2\ \Delta t\ / (m c_p) \tag{5}$$

$$\Delta T = (E^2 \Delta t / \upsilon)\, \omega\, \varepsilon'' / (\rho\, c_p) \tag{6}$$

where υ is the sample volume. By substituting the values of ε'', c_p and ρ for generic soil and Plexiglas [8, 9] (which, for a plastic, is a relatively strong microwave absorber) the relative heating rates can be calculated as

$$\frac{\Delta T_{soil}}{\Delta T_{plexiglas}} = \frac{\left\{ \dfrac{\varepsilon''_{soil}}{(\rho_{soil}\ c_{p\,(soil)})} \right\}}{\left\{ \dfrac{\varepsilon''_{Plexiglas}}{(\rho_{Plexiglas}\ c_{p\,(Plexiglas)})} \right\}} \tag{7a}$$

$$\frac{\Delta T_{soil}}{\Delta T_{plexiglas}} = \frac{\left\{ \dfrac{.2024}{(2\ g/cm^3\ 1\ J/kg)} \right\}}{\left\{ \dfrac{0.0148}{(1.2\ g/cm^3\ 1.38\ kJ/kg)} \right\}} = 11.3\ . \tag{7b}$$

Table 1. *Dielectric and mechanical properties of plastics.*

MATERIAL	ε'	ε''	ρ	c_p	APPLICATION	Ref
			kg/m³	***kJ/kg-K***		
Nylon-66 (Dupont)	3.16 – 3.33	0.036 (dry, 1MHz)	1.14			[9]
Bakelite	2.75 – 2.86		1.24-2.00		Fuse housing	
PVC	3.39 – 3.42		1.20-1.50	0.934		
Parafin wax	2.22	0.00022 (25°C, 3 GHz)	0.90		Explosive simulant	[8]
Parowax	2.25	0.00045 (25°C, 3 GHz)			Explosive simulant	[8]
Styrofoam	1.03	0.00010 (25°C, 3 GHz)			Thermal insulation, mechanical support	[8]
Plexiglas™	2.6	0.0148 (27°C, 3 GHz)	1.17-1.20	1.373-1.388		[8]
PFTE (Teflon)	2.1	0.000315 (25°C)	2.1-2.2	0.938		[8]
Lexan	3.0		1.2			
Low density polyethylene			0.910-0.925	2.315	Mine surrogate	
High density polyethylene	2.2		0.941-0.965	1.855	Mine surrogate	
Polypropylene homopolymer	2.2	0.003 (1 GHz)	0.90-0.91	1.79-1.805		
Polypropylene (15% carbon)		Low			PRB-M3-A1 (Belgium, O-ring)	[6]
Polypropylene (36% carbon)		Medium			PRB-M3-A1 (Belgium, bottom seal)	[6]
Natural rubber (no carbon)	2.3 – 3.0 (1kHz)	Low			Type 72 (Chinese, top cover)	[6]
Natural rubber (37% carbon)		Medium			Type 72 (Chinese, bottom seal)	[6]
1:2 syndiotactic polybutadiene		Medium			MC3 (Bulgarian)	[6]
Acrylonitrile-butadiene rubber	13.0 (1 kHz)	Low			O-ring on P4 Mk1 (Pakistan)	[6]
Polychloroprene (6% carbon)	9.0 (1 kHz)	Low			O-ring on SB33 (Italian)	[6]
Polychloroprene (25% carbon)	10.0	0.99			Rubber from VS-50	[6]
ABS	2.5	< 1E-4	1.02-1.08		Plastic from VS-50	[6]
High impact polystyrene	2.5	< 1E-4	1.03-1.06	1.194-1.220	Plastic from M14	[6]
Natural rubber (polyisoprene)	3.6	0.15	0.92-0.93	1.917	PMN (Russian, top cover)	[6]

Table 1. (cont'd) *Dielectric and mechanical properties of plastics.*

MATERIAL	ε'	ε''	ρ	c_p	APPLICATION	Ref
			kg/m^3	$kJ/kg\text{-}K$		
PVC (with phtalate ester plasticiser)	2.9	0.09	1.16-1.35		PMN (Chinese, top cover)	[6]
Water	76.7	12.042 (25°C, 3 GHz)				[8]
Dry sand	2.55	0.0158 (25°C, 3 GHz)				[8]
Moist sand (3.88% moisture	4.40	0.2024 (25°C, 3 GHz)				[8]

The result of eq. (7b) indicates that the heating rate for soil is, in general, significantly larger than for plastics. Therefore, the soil around the mine or mine surrogate will heat at a faster rate than the target itself.

One factor may help alleviate the above problem. The dielectric constant of a material can be strongly influenced by temperature. In microwave heating applications, *thermal runaway* is defined as an uncontrolled rise of the temperature due to the positive slope on the ε'' versus temperature curve. An example of such a curve is given in Figure 2 for Nylon [10] at 3 GHz. At approximately 80°C, the loss factor of Nylon begins to increase dramatically. This causes further absorption and, in turn, additional heating. This cycle repeats to further increase the temperature. This effect may be present in some mine bodies or explosives, but the electrical characterization of these materials is generally not available.

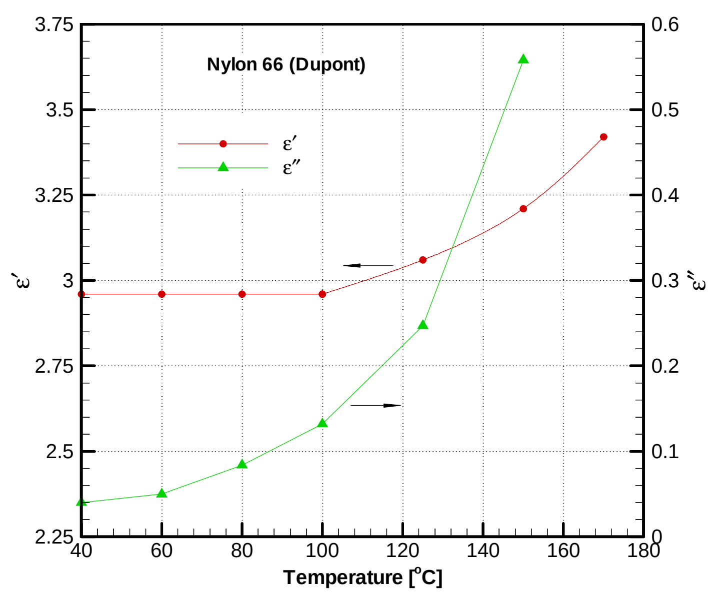

Figure 2. *Example of thermal runaway for Nylon.*

2.2 Dielectric Properties of Explosives

One possible mechanism of mine neutralisation is direct RF heating of the explosive material. The temperature change can be calculated using eq. (5) and the relevant constants from the list compiled in Table 2. It should be noted that ε' (and probably ε'') are a function of the density of the explosive [6]. Unfortunately, like in most plastics, explosive materials are generally non-hygroscopic [11] and ε'' is very small [6, 12]. Therefore, the heating rate for most explosive materials is relatively low.

The literature provides some information about the dielectric properties of explosives. In the study by Hasue *et al.*[12], the use of a soda-lime glass tube as a sample holder complicates the interpretation of these results. Bird and Czigledy [6] report that the rate of heating for the sample tube was larger than many samples and may have been the source of ignition. As such, the values obtained from this source must be used with caution.

Two primary explosives that are used in small quantity in the fuse train of a mine, lead azide and black powder, may have a direct susceptibility to microwaves and could be heated to their ignition point. Unfortunately, the dimensions of the primary explosive content are generally smaller than $\lambda/2$ and the coupling of microwave energy into the sample is very inefficient. Furthermore, the primary explosive is often enclosed in a metal housing that also shields it from the microwave energy. As a result, it is unlikely that direct initiation of these primary explosives can be achieved within a metal landmine. On the other hand, if the charge is placed in a non-metallic or low metal content mine, it may be susceptible.

2.3 Microwave Interaction with Metals

In general, microwaves interact strongly with metallic objects. The key to coupling energy efficiently is to have an object with physical dimensions that are a significant fraction of a wavelength and to align it in the direction of the impinging electric field. If these conditions are met, substantial currents can be induced. Wherever there is current, an accumulation of charge and a strong localized electric field take place that can create heating effects and arcing in the surrounding material. The probability of arcing is greatly enhanced if the metal is sharp or pointed, as in the case of a firing pin, spring or thin wire. This may be a useful means of igniting the primer in a mine or exposing a trip wire.

2.4 Empirical Models for the Electrical Properties of Soil

Ideally, the dielectric loss (at microwave frequencies) in an explosive material would be very high and much larger than that in the materials surrounding the mine. These circumstances would result in a very efficient transfer of energy. Unfortunately, the opposite is true; the losses in plastics/explosives tend to be low and the soil surrounding the mine tends to absorb the energy more efficiently, see Table 1 and Table 2. Thus, a comprehensive understanding of the electrical properties of soil is required.

In general, the dielectric constant of a soil mixture is a function of frequency, temperature, moisture content and bulk soil density/texture. This subject was dealt with in much more detail in a previous DRE Ottawa study [4] and, therefore, it is only summarised below.

Table 2. *Dielectric and mechanical properties of explosives and stab sensitive compounds (0.5-3 GHz)*

EXPLOSIVE [Ref.]	ρ	ε'	ε''			$T_{melting}$	E_{spark}	$T_{ignition}$	c_p	APPLICATION
	g/cm^3		*min*	*2.45 GHz*	*max*	℃	*J*	℃	*Cal/g/℃*	
TNT [A]	1.6	2.3	$< 5.0e^{-4}$	$3.8e^{-3}$	$4.0e^{-2}$					
TNT [B]	1.55					80				Bursting or main charge
TNT [C]	0.86	2.0		$2.4e^{-4}$		80.75	4.0	288-330		
TNT [D]						81		295-300	0.328 (20°C)	
Tetryl [A]	1.6	2.4	$< 5.0e^{-4}$			129-130			190	
Tetryl [B]	1.57									Booster
Tetryl [C]	0.92	2.3		$1.3e^{-3}$		129.45	3.83	190		
Tetryl [D]						130		201-212	0.223 (50°C)	
RDX [A]	1.6	2.7	$< 5.0e^{-4}$		$2.0e^{-2}$	200-204				
RDX [B]	1.65							200-204		Booster or explosive cord
RDX [C]	1.04	2.5		$1.7e^{-3}$		204.1	0.87	200-220		
RDX [D]						204		229	0.298 (20°C)	
Comp B [A]			$5.0e^{-3}$		$4.0e^{-2}$					
Comp B [D]						78-80		177		Main charge
Comp B [E]								177		
PETN [A]	0.9	2.4	$< 5.0e^{-4}$		$4.0e^{-2}$					
PETN [B]	1.6					140				
PETN [C]	0.98	2.1		$6.3e^{-3}$		141.3	0.75	200-201		Booster or explosive cord
PETN [D]						141		203	0.24 (25°C)	
PETN [E]	0.86							158	0.26	
Tetracene [A]	1.2	2.9	$< 5.0e^{-3}$		$7.0e^{-2}$					
HMX [C]	1.11	2.4		$7.0e^{-5}$		276-277	1.42	241-253		Booster
HMX [C]								279-281	0.248 (25°C)	

Table 2. (Cont'd) *Dielectric and mechanical properties of explosives and stab sensitive compounds (0.5-3 GHz)*

EXPLOSIVE [Ref.]	ρ	ε'	ε''			$T_{melting}$	E_{spark}	$T_{ignition}$	c_p	APPLICATION
	g/cm^3		*min*	*2.45 GHz*	*max*	°C	*J*	°C	*cal/g/°C*	
Ammonium nitrate [C]									0.414 (50°C)	Booster
Ammonium nitrate [D]	1.09	4.5		$2.8e^{-3}$		80				
Lead styphnate [A]	1.3	4.4	$< 5.0e^{-4}$		$3.0e^{-2}$					Primer, detonator
Lead styphnate [B]	3.1					Explodes				
Lead styphnate [D]						Expl.311C		293	0.164 (50°C)	
Lead styphnate [E]	1.65							249	0.164	
Black powder [A]	0.74							> 200	0.26	Igniter, fuse powder
Black powder [D]								510	0.345 (25°C)	
Lead azide [A]	3.2	8.0	$5.0e^{-2}$		0.15					Primer, detonator
Lead azide [D]								383	0.11 (50°C)	
Lead azide [E]	1.69					Decomp.		280		
Lead Dioxide [C]			95		377					Stab sensitive compounds
Lead thiocyanate [C]			$< 2.0e^{-4}$							
Antimony sulphide [C]			0.13							
Potassium chlorate [C]			$< 2.0e^{-4}$							
Barium nitrate [C]			$< 3.0e^{-4}$							

[A] Bird, R. and Czigledy, R.C., Feasibility of using microwave radiation to neutralise non-metallic landmines, DSTO Report, 1995.

[B] Bolz, R.E. and Tuve, G.L., Handbook of tables for applied engineering science, CRC Press, 1973.

[C] Hasue, H., Tanabe, M., Watanabe, N, Nakahara, S. and Okada, F., Initiation of some energetic materials by microwave heating, Propellants, explosives and pyrotechniques 15, 181-186, 1990.

[D] Patel, D.L., Handbook of landmines and military explosives for countermine exploitation, Belvoir RDEC, Technical report BRDEC-TR/2495, 1992.

[E] Murray, D.A., Wiegand and Pinto, J., High power pulsed microwave susceptibility of eight energetic materials and two fuels, Technical report ARAED-TR-91003, 1991.

Ideally, one would like to derive the value of the dielectric constant given only the soil composition, moisture content, etc. A number of models exist for such an endeavour, but under most practical circumstances, the input parameters required are not easily available or are poorly suited for the frequencies of interest. As such, it is easier, and often more accurate, to work from a simple empirical formulation. These expressions are generated from curve fits to experimental data using 2nd order polynomials. For example, Hallikainen *et al.* [13] used independent fits of ε' and ε'' for sandy soil at a frequency of 2.45 GHz as follows:

$$\begin{aligned} \varepsilon' &= 1.709 + 76.08\ m_g + 158.8\ m_g^2 \\ \varepsilon'' &= 0.087 + 8.471\ m_g + 26.51\ m_g^2, \end{aligned} \qquad (8, 9)$$

where m_g is the gravimetric moisture content of the soil. The skin depth can be shown to be

$$\delta = \frac{c}{\omega}\left[\frac{\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]\right]^{-1/2}, \qquad (10)$$

where ω is the angular frequency and c is the speed of light. The power loss (P) in dB/cm can be expressed as

$$P = -0.086859\ \frac{\omega}{c}\left[\frac{\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]\right]^{1/2}. \qquad (11)$$

Using Eqs. (8) - (11), the skin depth and power loss can be expressed as a function of soil moisture content.

Measured values for the heating rates are given in Figure 3. These values pertain to an abruptly terminated wave-guide situated 2 cm above the sand (3% gravimetric moisture content) surface with the magnetron operating at 5kW. Measurements were simultaneously made at depths of 1, 5 and 10 cm.

The shapes of the curves reveal the nature of the heating process. The magnetron was turned on at approximately the 1-minute mark. At that point the soil temperature, even at the 5-cm depth, rises abruptly to 100^{o}C in -1 minute. The latent heat of vaporisation must then be overcome and the temperature holds steady until all of the water is converted into steam. Once this happens the temperature is free to increase again, as indicated on the curves.

Heating rates are generally not linear processes primarily because the associated loss mechanisms vary with temperature (convection, diffusion) and temperature to the fourth power (radiation). In addition, the attenuation of the microwave power is exponential with soil depth. This can be seen in the fact that the plateau region at 100^{o}C varies as a function of depth, and the heating rates below 100^{o}C (particularly at the 10 cm depth) vary with time as the moisture is removed from the soil levels above. The decreasing heating rates above 100^{o}C (which is most prominent at the 1 cm depth) are primarily due to convection cooling.

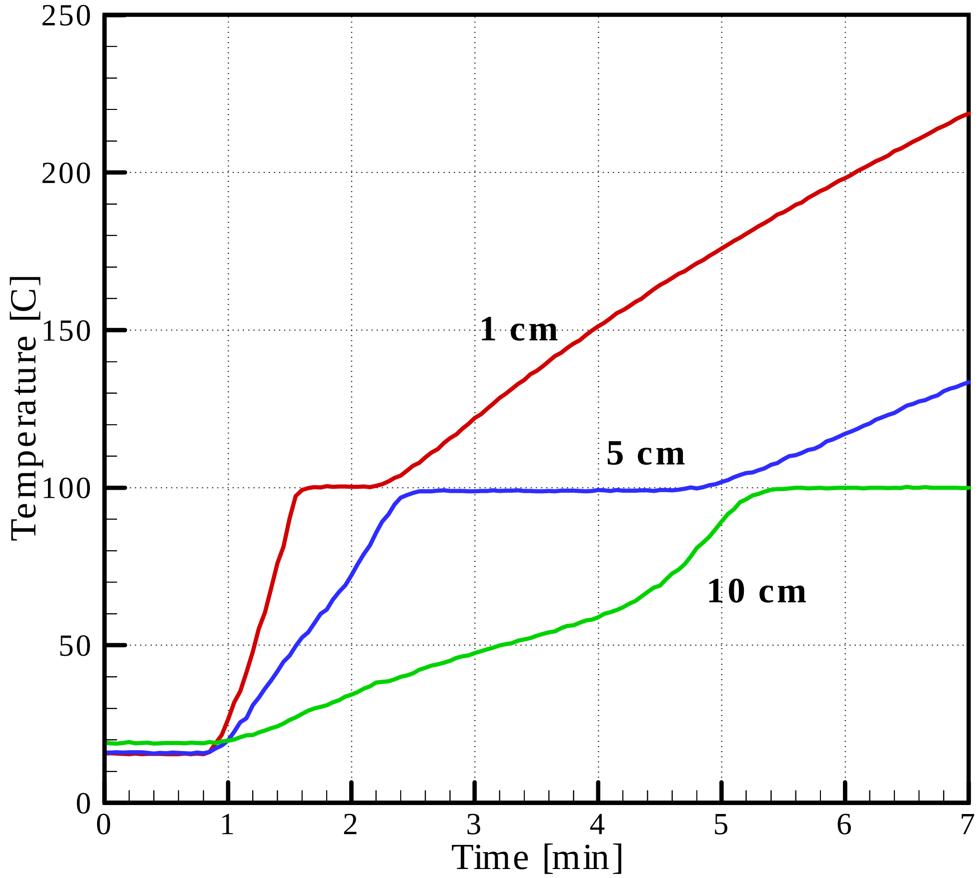

Figure 3. *Soil heating at three different depths in sand – moisture 3% and 5 kW power.*

3. Surrogate Studies

The most reliable way to determine the feasibility of HPM mine neutralisation is through experimentation. Initial studies were therefore carried out at DRE Ottawa using surrogate targets that were constructed from plastic discs with dimensions representative of typical AP landmines. These surrogates were buried 10 to 50 mm below the ground surface.

The setup used for the microwave illumination during the present experiments was similar to that used during previous experiments, as depicted in Figure 4. The 5 kW of energy from a Cober Electronics Model 6F magnetron operating at 2.45 GHz was directed using a standard WR284 waveguide. Unlike in Figure 4, the waveguide was terminated abruptly 10 to 30 mm above the soil surface instead of being terminated by a horn antenna. By terminating the waveguide abruptly above the soil surface, the power density delivered to the target was maximized. Power meters and directional couplers were placed in-line with the waveguide to measure the transmitted and reflected power. The results were recorded directly to a PC using the GPIB.

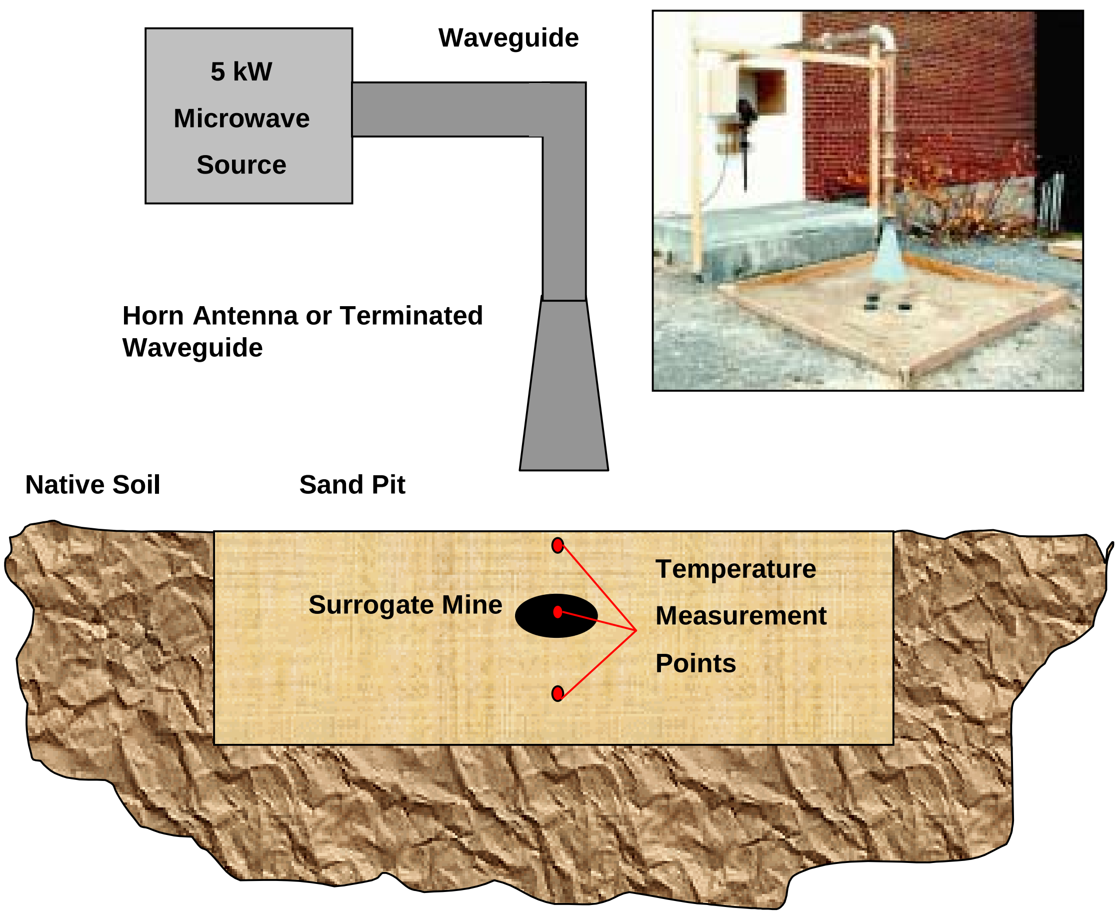

Figure 4. *Setup used for heating study with AP mine surrogates.*

3.1 Surrogate Targets

Detailed information on the plastics used in AP landmines was not available at the time of this study. It was therefore assumed that, for cost reasons, mine manufacturers use materials such as high-density polyethylene, low-density polyethylene or polypropylene because these materials are inexpensive, readily available and easy to injection mould. A further side benefit of using these materials for this study was that they are poor absorbers of microwaves; hence they would not bias the results towards an outcome that would be too optimistic.

In addition to being used alone, some of the surrogate targets were used in combination with other materials to emulate specific AP landmine types that would be used in the subsequent field trials at DRE Suffield, as will be discussed in Section 4. Figure 5 (left side) depicts a surrogate target disc with a Bakelite plug on its surface to emulate the fuse housing of a PMA-2 landmine. A second disc (right side) has a rubber gasket covering its top surface to emulate the PMA-3 landmine.

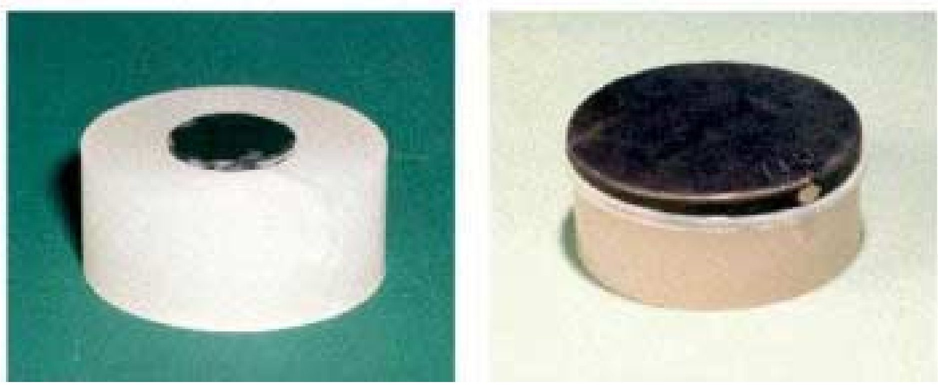

Figure 5. *Surrogate targets used to emulate AP mines. (Left side) with bakelite disk on upper surface and (Right side) covered with rubber cap.*

3.2 Experimental Conditions

In order to properly characterize the heating of the surrogate targets, it was necessary to carefully control as many of the test parameters as practically feasible. The principle variable was differences in target geometry and materials, but it was found that soil conditions were a major factor that could influence the outcome of the experiments. Another factor that could influence the results was the location of the temperature measurements. Temperature was the easiest way to quantify the heating rates. Finally, it was known that the abrupt termination of the waveguide would affect the power density distribution. These three major factors are therefore discussed in more details below.

3.2.1 Soil Type and Moisture Content

Soil samples from the field are generally heterogeneous in terms of particle sizes and composition. However, previous experiments had indicated that moisture was the main factor that determines the dielectric constant of soil at the 2.45 GHz frequency used in these tests. It was therefore decided to use uniform construction sand for this study. Particle size is reasonably constant with little clay or silt being present in the mixture and it is an easy mixture to handle, particularly when very wet.

The surrogates were mainly tested at a soil moisture content of ~3%. The samples were prepared by mixing a measured volume of tap water to a measured volume of dry sand. A look-up table had been prepared to ease the process and to obtain specific moisture values. The “calibrated” soil was then placed in an excavated volume with dimensions 2 m by 2 m by 0.6 m deep centred under the microwave source.

The mine surrogates described above were buried in sand, as shown in Figure 6. The moisture content of the sand immediately below the applicator was varied during the measurements. Given that the soil pit was outdoors, it was soon found out that the meteorological conditions could affect the experiments. Thus, an insulated wooden structure was placed around the pit to minimise the environmental variations (i.e. varying cooling rates due to intermittent wind, rain etc. during a particular experiment, or weather variations on a day-to-day basis).

Figure 6. *Surrogate target with temperature probes buried in moist sand within the control pit.*

3.2.2 Probe Calibration

Fibre optic thermometers (Photonetics MetriCor 2000) were used to measure temperatures at various locations. These probes are constructed in such a way that they can be exposed to extreme microwave fields without degradation of performance. This makes it possible to make real time measurements of soil or plastic heating rates. Temperature values were recorded directly to a PC via a GPIB.

One problem with the thermometers is that they are enclosed in a 3 mm diameter, closed-tip, ceramic sleeve for mechanical protection. When measuring inside a surrogate sample, they were further enclosed in a quartz tube to prevent the molten plastic from bonding to the probe tips. As a result, there is a finite, medium-dependent response time associated with the probe. Optimal thermal contact is made with very wet materials and the response times for the thermometers are negligible under these circumstances, see Figure 7. The other extreme is in a medium that acts as a good thermal insulator (like the quartz sleeve) where the response time can be several minutes. The response time is an important consideration when evaluating the experimental results throughout this report.

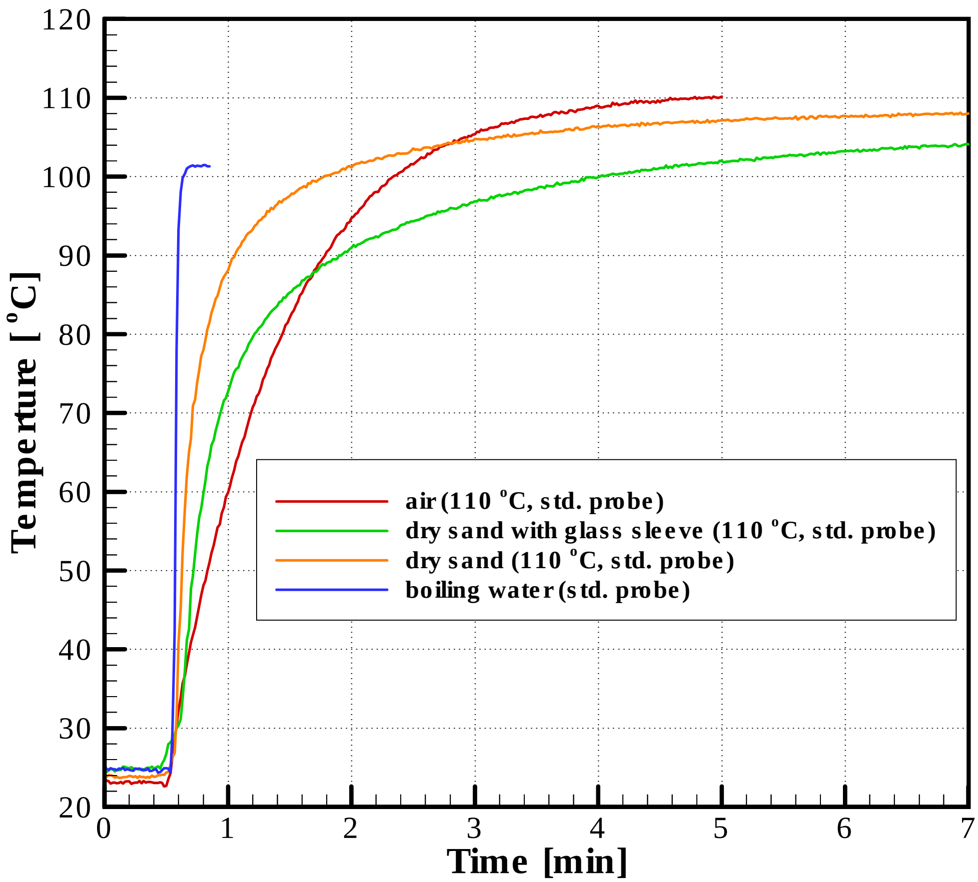

Figure 7. *Temperature response of probes for various medium.*

3.2.3 Power Density

The abrupt termination of the waveguide made it a poor radiating antenna because its small aperture generates a large dispersion of the microwave energy. As a result, the power density varies greatly with the distance from the end of the waveguide, i.e., as a function of soil depth. Calculation of this power density and the associated electric field is difficult because the close proximity between the applicator and the soil interface significantly increases the interaction and feedback into the system. In addition, the reflection at the soil interface and power absorption in the soil strongly depend on the soil moisture content, which varies significantly during the course of an experiment as vaporisation takes place. Finally, the presence of a surrogate target below the waveguide significantly alters the distribution of power by scattering and absorbing energy.

To establish the power density, infrared (IR) measurements of the heating patterns were made down to 50 mm below the soil surface. This was accomplished in a two-step process, as indicated in Figure 8. Initially, the exposure area was prepared by placing a series of wooden frames below the waveguide. These rectangular frames are 1 cm thick and open in the middle, like an empty picture frame, to minimize the interaction with the microwave beam. The open area was carefully filled with the same dry sand as that in the surrounding pit. A layer of microwave plastic wrap (Saran Wrap™) was used to separate each layer.

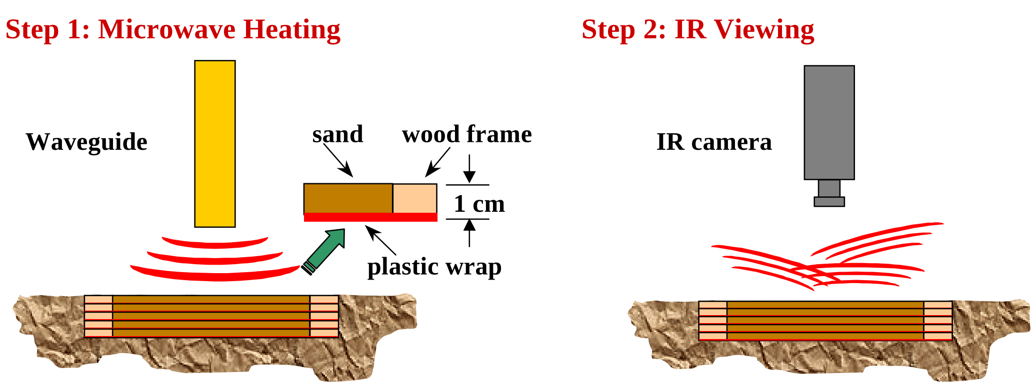

Figure 8. *Process used to measure power density at the end of an abruptly terminated waveguide.*

The entire assembly was then exposed with the microwave waveguide at a height of 25 mm, similar to the trials. The exposure time was minimised (2 minutes) to prevent convection and conduction cooling from excessively distorting the profile, but was long enough to provide adequate dynamic range for the IR camera (Agema Model #550). The IR image acquisition was started approximately one minute after completion of the microwave exposure, the minimum time required to remove the waveguide and position the camera. Immediately after photographing a layer, the frame and sand overburden was removed to expose the next layer. The plastic wrap facilitated a very quick and efficient removal of the soil. The entire imaging process took approximately two minutes. Calibration targets were also photographed to establish the dimensions of the images. This produced a series of images of soil temperature at 10 mm increments, as shown in Figure 9.

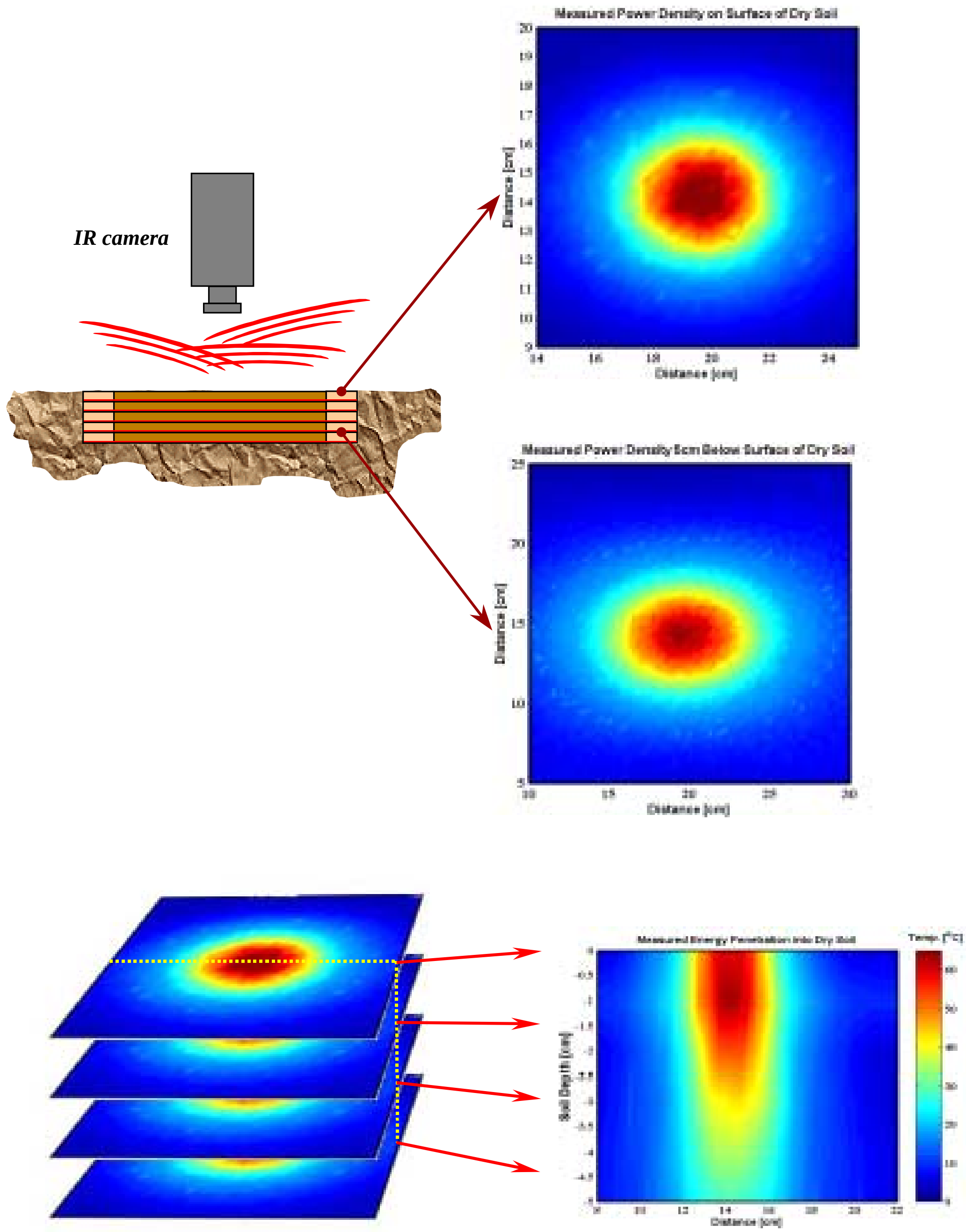

Figure 9. *Images of the soil temperature from an IR camera and numerical interpolation of profiles.*

The images of the soil temperature at 10 mm increments were digitized and stored in a matrix format. A cross-sectional cut could then be numerically established in any vertical plane. The image in Figure 9 has been numerically interpolated to fill in the spacing between the layers. From this image the variation in temperature, hence power levels, can clearly be seen. The exposure area is what could be described as a pencil beam with a width of approximately 50 mm and a depth of several tens of mm. It is interesting to note that the area approximately 10 mm below the soil surface is the hottest because convection cooling removes heat from the soil surface.

These measurements produced images of the temperature profiles in the soil. Ideally, the microwave power density is the relevant figure of merit since it allows the extrapolation of the results to larger microwave source powers. This value can be estimated as follows: The forward and reflected power in the waveguide was measured using directional couplers, hence the power leaving the waveguide is known. The reflection of the microwave energy from the soil surface can be estimated based on the dielectric properties of the soil, therefore, the total power impinging on the soil can be estimated. Since the temperature change on the soil surface is known to be proportional to the power levels, then the temperature profile should be the same as the power profile. The power density can be estimated by integrating the area under this curve and adjusting the peak values such that the total power levels match the values determined above. This technique has been used to derive Figure 10, the power density on the soil surface for an abruptly terminated waveguide at a height of 25 mm. From this image it can be seen that the peak power density is approximately 150 W/cm^2 but drops off within 20 mm to about 50 W/cm^2.

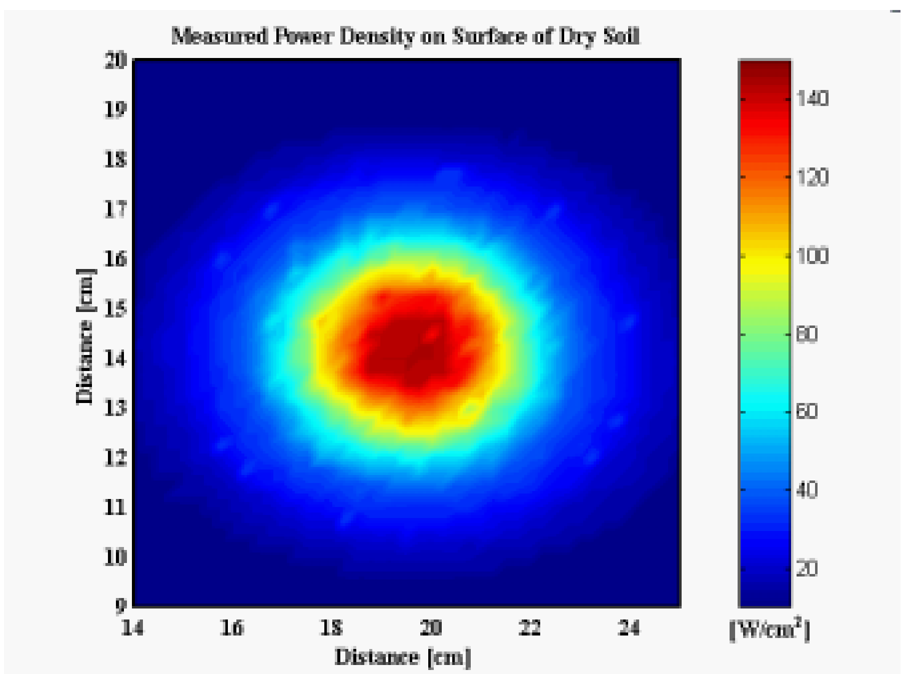

Figure 10. *Power density on the soil surface for an abruptly terminated waveguide.*

3.3 Practical Considerations and Problems

The influence of meteorological conditions was mentioned above. The heating study was initially done in an outdoor pit. As a result, the heating curves generated were very susceptible to convection cooling from the wind, which made it difficult to compare the results from one run to another because of excessive variations in the test conditions. At times, there were significant temperature fluctuations during the same run, particularly at the 1-cm depth. Short periods of cooling were even observed. Similar problems were encountered with periodic rain showers. Thus, to minimize the influence of meteorological factors, a large, insulated wooden structure was erected around the sandpit. This greatly limited the influence of wind and rain but still allowed normal convection to take place. By heating the test area with a small, electric space heater, the structure provided the additional advantage that testing could take place well into the winter months.

Another problem encountered during our experiments is that steam from the evaporation of moisture in the soil and smoke from the burning plastics would enter the waveguide applicator. The presence of these impurities in the waveguide would then absorb microwave energy, become superheated and cause three problems:

a. It decreased the energy reaching the soil;

b. It caused the waveguide to heat up significantly; and

c. It altered the impedance of the waveguide, which increased the reflections back to the magnetron.

The last condition occasionally caused the magnetron to shut off if the reflections became too large. The solution to these problems was to place a layer of plastic wrap or a 1-cm Styrofoam insert at the end of the waveguide.

There were a few difficulties with the use of sand as the test soil. First, because dry sand tends to flow, it was difficult to physically place the probe. As a result, there is always a 2-3 mm uncertainty with the probe depths quoted. In wet soil, the water boiled and resulted in slumping of the soil surface as the moisture was driven out. This caused abrupt changes in temperature as the probe changed positions. Finally, the probes themselves are 3 mm in diameter and could interfere with the local soil parameters, absorption and diffusion rates.

3.4 Results

These experiments demonstrated conclusively that soil heating to typical mine depths could easily be achieved. Figure 7 shows the characteristic soil-heating rate for the moist sand used in these tests. Recall that these are free-field values, i.e., without a surrogate, and that the soil dielectric constant strongly depends on soil moisture content. The best penetration of the microwaves into the soil medium occurs with dry soil. In addition, the soil-heating rate varies significantly with exposure time.

Figure 11 shows that the surrogate targets could be heated to well above their deformation temperatures within approximately 5 minutes. This is true even though the samples used were constructed from poorly absorbing plastics. The discs were in a gelatinous state when they were removed from the soil and they could be crushed by hand. From this result, it is suggested that significant deformation of a plastic mine case would occur, particularly if it is constructed from dissimilar materials with different absorption and thermal expansion rates.

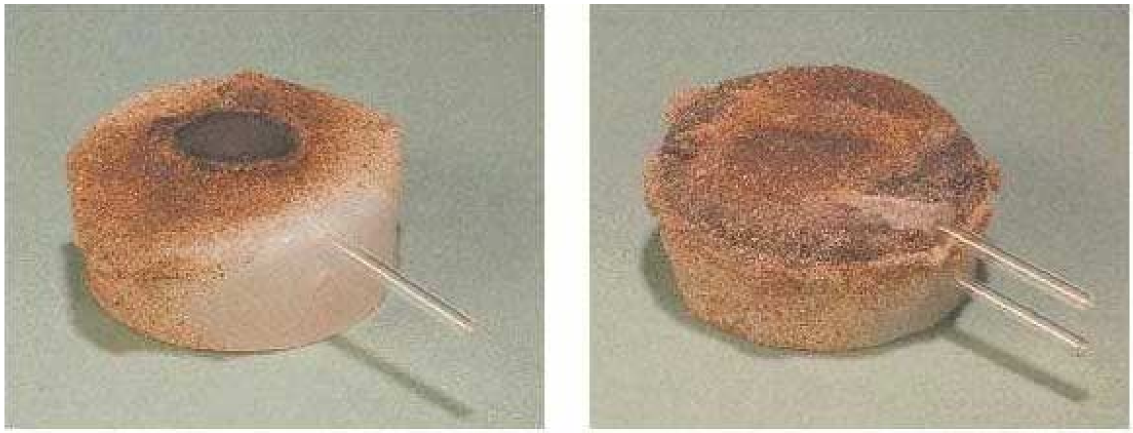

Figure 11. *Surrogate targets used to emulate AP mines following exposure to microwave radiation. (Left side) with bakelite disk on upper surface and (Right side) covered with rubber cap.*

Figure 12 is a plot of the temperature rise in three sample discs. One is a disc of polypropylene used in isolation while the other two discs had been modified to emulate a PMA-2 and PMA-3 AP landmines, respectively. It had been anticipated that the dielectric properties of the plastics would vary with temperature because of thermal runaway. However, the rate of temperature change is approximately linear, thus indicating that there was no thermal runaway. One possible explanation is the fact that the response time of the temperature probe is slow on the time scale of this experiment or that the duration of the experiments should have been increased.

One interesting observation is that although bakelite and rubber are strong microwave absorbers, their influence was limited to the upper portion of the surrogate target. The centre of the target was not strongly affected. This poor result was not expected to limit the applicability of the neutralisation technique since the fuse is often located on the top of a mine and that the highly temperature-sensitive initiator is located within the fuse.

It is also reasonable to expect that the explosive content of a real AP landmine would heat in a similar manner as the plastics used for this study. The initiator and booster materials in the fuse may also be particularly susceptible to heat. As such, the results of the surrogate mine heating experiment indicate that detonation of a real mine is feasible and highly probable.

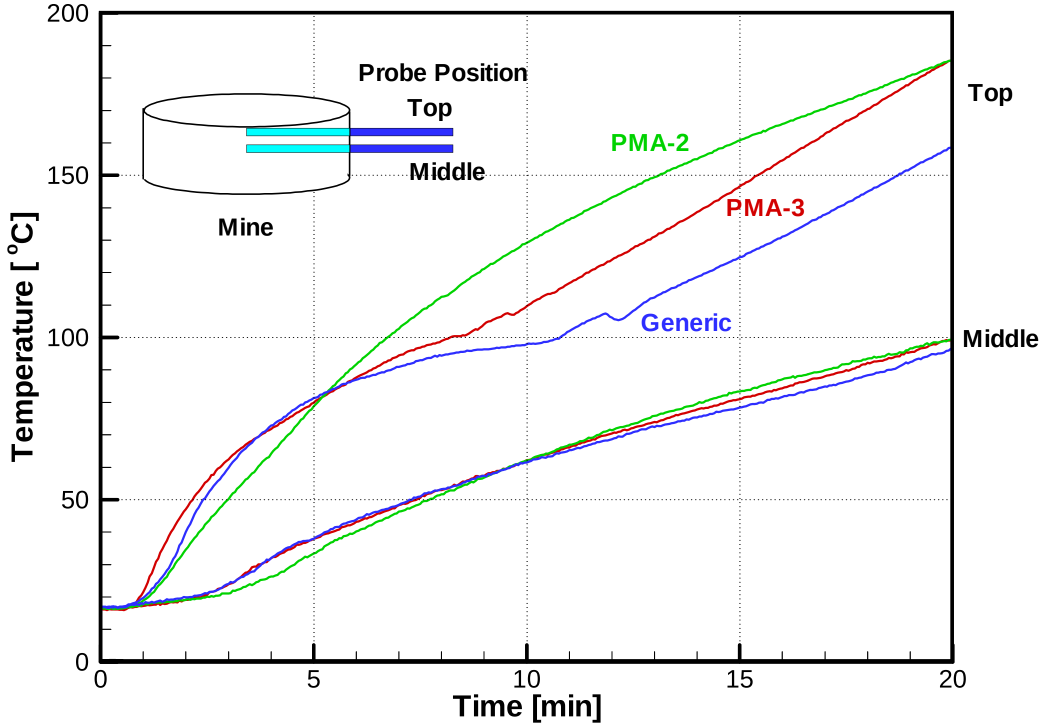

Figure 12. *Temperature response at two locations for the three surrogate target configurations.*

4. Live Mine Trials

The results from the heating study conducted against surrogate landmine targets indicated that there was significant potential for HPM neutralisation of landmines. It was therefore decided to proceed with trials against live mines. Ideally, these experiments would be done with a standoff distance of several meters, but that would require sufficient power density and a delivery system that did not exist at the time. Furthermore, the design and construction costs of such a HPM system was prohibitive and could not be justified without first demonstrating the technical feasibility of the technology. Because of these constraints, it was decided to perform a limited number of experiments using a waveguide applicator, as in the surrogate study. Although there was a large probability that the applicator would be destroyed by explosion because of the close proximity of the waveguide to the mine, this approach represented the most practical solution within the budget available.

Joint DRE Ottawa/Suffield trials with live landmines were performed at DRE Suffield in April 1997. The technique to apply microwave power to the live landmines was similar to that used during the surrogate study. However, since real explosives was be used, there was a need to adapt the overall test layout and the experimental procedures to the new situation. The details about the experimental setup are given in section 4.1. The tests were performed against three mine types that are described in section 4.2. As with the initial study with surrogate targets, problems were encountered during these experiments, which required practical solutions as discussed in section 4.3. Section 4.4 presents the results of the nine experiments conducted against live landmines. Finally, section 4.5 describes the results of supplementary experiments where inert new generation electronic landmines were exposed to HPM.

4.1 Experimental Setup

The use of explosives within a research environment where materials are pushed to new limits requires the utmost care. Safety is paramount. The experimental layout was therefore designed to minimise the handling of the test specimen after exposure to microwave radiation. In addition, there were concerns about the survivability of the magnetron to shock loads generated by an explosion. Much effort was expended in the design of appropriate protective measures for the equipment. The details of the test layout and the protection are given below. Other factors such as soil conditions, power density delivered to the target and the instrumentation used during these feasibility trials are also described in this section.

4.1.1 General Layout

The experimental layout was designed so that once a target landmine had been buried in the test soil, there would not be any need for personnel to approach it until the demolition phase, well after the experiment was completed. The layout is shown in Figure 13. It consists of three sites that were dedicated to irradiation, soil evacuation and demolition, respectively. Large concrete blocks were used as blast barriers in case of a post-irradiation detonation of the landmine. Figure 14 is a schematic of the overall HPM system where the magnetron and a water-cooling system were mounted on a trailer that was placed next to the irradiation site behind a blast shield. The HPM power supply with its associated controls, along with a data acquisition system and computer, were installed in a blast-resistant structure located several meters away. During a test, all personnel were confined to the blast-resistant structure.

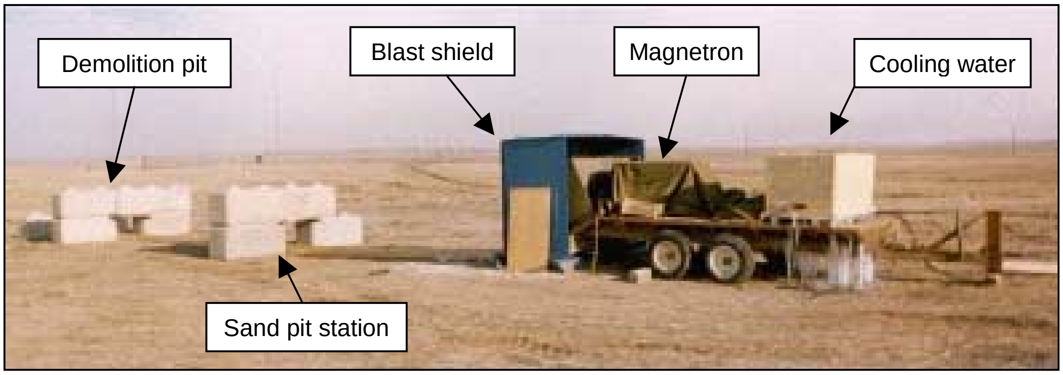

Figure 13. *General layout of the experimental setup for trials against actual landmines.*

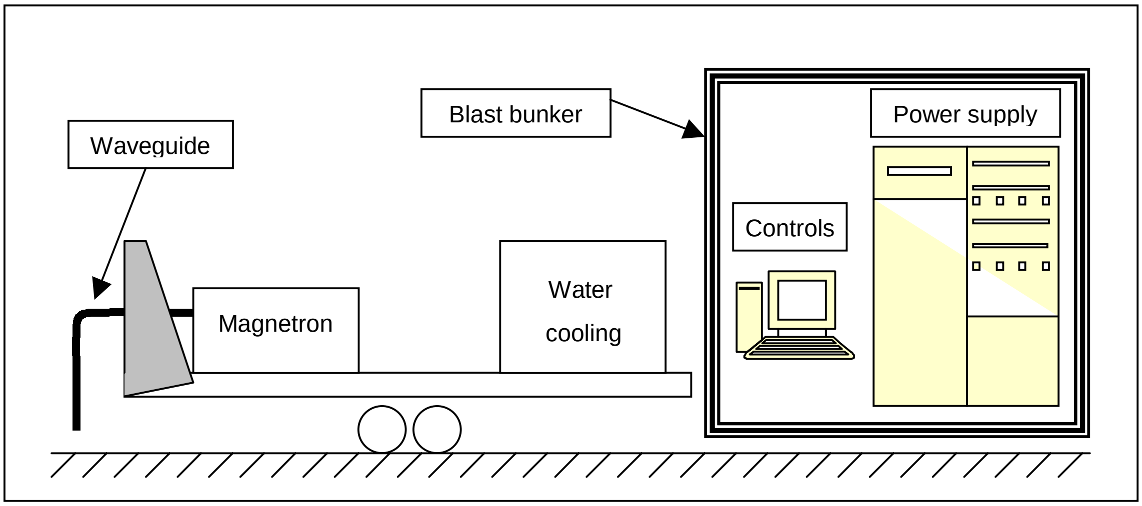

Figure 14. *Schematic of HPM arrangement for tests against actual landmines.*

Figure 15 shows the waveguide protruding through the blast shield and terminating abruptly above the surface of the soil. The soil was contained in an expendable soil box constructed of plywood. The box was located in wooden guide rails and was attached to an electric winch located at the other end of the rails, approximately 50 meters away. The winch was operated remotely from the confine of the bunker. Closed-circuit video provided feedback to control the winch.

The overall test procedure consisted of placing the wooden box next to the blast shield such that the waveguide was approximately at the centre of the soil. The soil was then added and all non-essential personnel moved to the bunker. A target landmine or landmine component was then buried in the proper orientation close to the end of the waveguide. The remaining personnel then moved to the bunker and irradiation of the target started. The process was recorded on video and data was logged onto the computer. Once the microwave exposure was complete, assuming that detonation of the landmine had not occurred to destroy the wooden box, the box was pulled to the soil evacuation pit, Figure 16. The bottom of the box was an open nylon mesh (made of fishing line), as shown in Figure 17. It should be noted that sand spilled out as the box assembly travelled along the guide rails, and the box completely

Figure 15. *Waveguide exiting through blast shield and down to moveable sand box on guide rails.*

Figure 16. *Sand evacuation pit designed to separate burnt landmine components from soil.*

Figure 17. *Bottom of the wooden box laced with fishing line to allow soil escape.*

emptied at the pit. A compressed air cylinder and jets could be used to remotely blow any sand off the mine remnant. The entire process was monitored and recorded from a safe location by video. After observing the condition of the mine then, if necessary, the entire box assembly could be pulled to the demolition site for explosive disposal at a later time.

4.1.2 Blast protection

A magnetron is normally not designed to operate in a shock and blast environment. There were therefore serious concerns about the survivability of the magnetron to the blast loads generated from the detonation of a landmine at the open end of the waveguide. The closed geometry of the waveguide is favourable to the propagation of blast energy. The strength of the blast wave would not decay to safe levels over the distance separating the landmine and the resonance cavity of the magnetron. A solution was therefore needed that would prevent propagation of blast energy while remaining transparent to microwave energy.

A Teflon plug, which was designed by Dr. S. Kashyap and M. Burton of DRE Ottawa, was incorporated into the waveguide to protect the magnetron. The mechanical details of this plug are shown in Figure 18. It was installed just past the elbow of the waveguide. The microwave transparency of the plug is at the operating frequency of the magnetron is shown in Figure 19. Another problem was the transmission of a shock through the magnetron structure. This was addressed by mounting the magnetron in a shock-isolated box on the trailer. The shock and blast resistance of the magnetron had been evaluated in preliminary blast tests at DRE Suffield. The results from these blast trials will be described in a separate report.

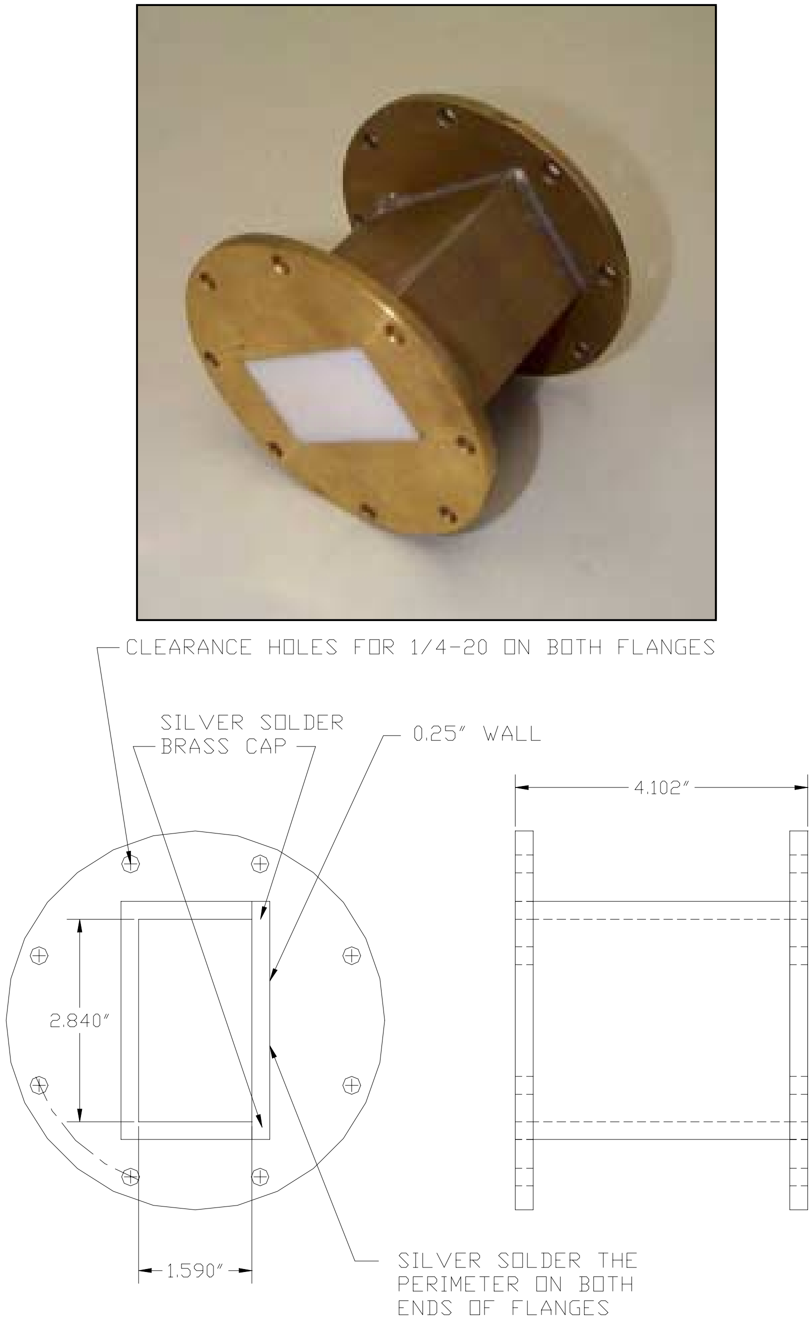

Figure 18. *Teflon plug transparent to microwaves, but designed to stop blast wave propagation.*

The waveguide was attached to the Teflon plug using nylon bolts at the elbow section. This design feature allowed failure of the bolt under the force of a detonation near the open end of the waveguide, thus limiting the transmission of bending moment through the remainder portion of the waveguide, which was attached to the magnetron through a 0.6 m long section of flexible waveguide. Another feature of the plug was that it was composed of several 25 mm thick pieces. It was therefore possible to recycle the plug assembly after a blast by replacing the first damaged section. This was necessary because the presence of carbon contaminants on the surface of the plug would cause arcing and a heat build-up that would result in power reflections that could eventually shut down the power supply (a safety mechanism of the system).

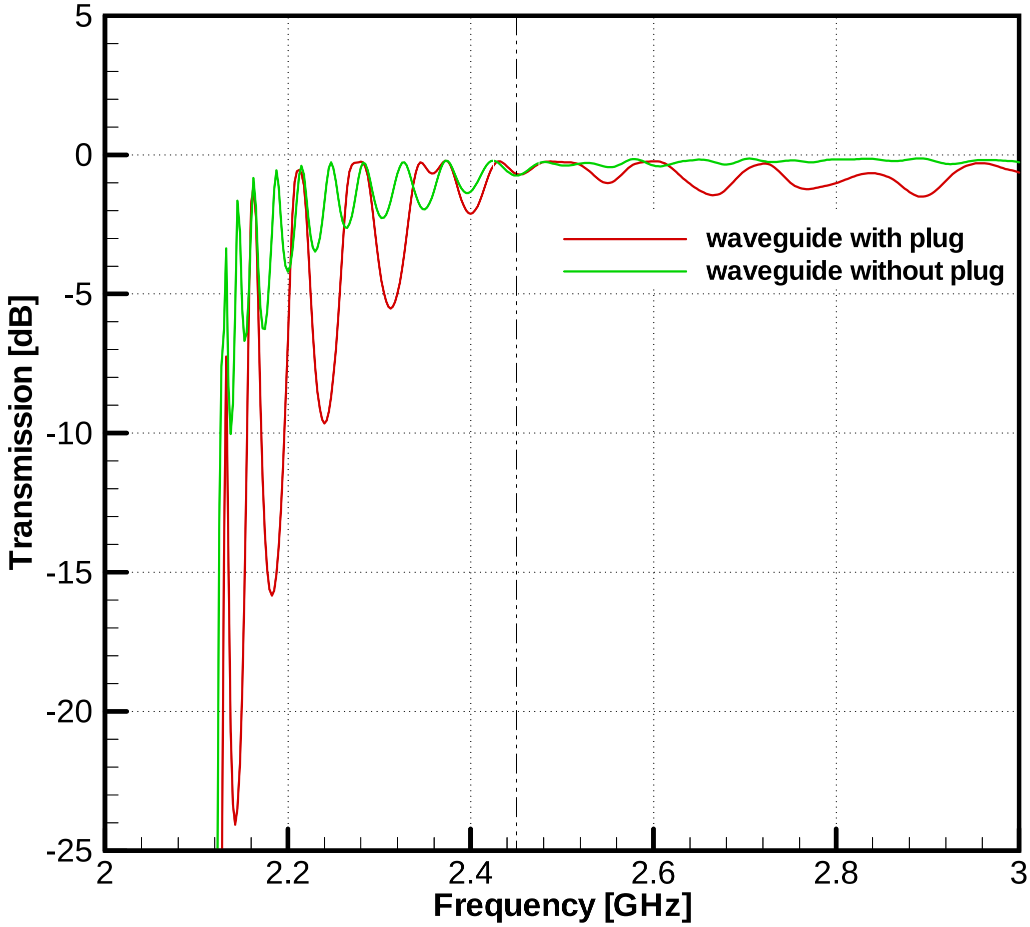

Figure 19. *Measured transmission of microwave energy in a waveguide with and without the plug.*

4.1.3 Soil Type and Moisture Content

The remote nature of these experiments required the remote evacuation of the soil within the box so that the damage to the landmine could be observed visually by video. This dictated the use of dry sand that would easily flow through the bottom mesh of the wooden box under normal gravity conditions. The sand selected is manufactured for industrial sandblasting and has is a very uniform particle size. There is no clay, no silt and no moisture present in the mixture. By comparison, field samples of various soils are generally very heterogeneous and contain moisture.

Prior to the start of experiments with landmines, a simple soil heating test was performed on the dry silica sand to compare its heating rate to that measured previously in moist sand at

DRE Ottawa, as shown in Figure 7. The heating rate is linearly dependent on the applied power. During the DRE Ottawa experiment, the power setting was 5 kW while the experiment at DRE Suffield was at 4.5 kW, thus the heating rate would be 90% of that observed previously. Figure 20 shows that, as expected, the heating rate of dry sand is very slow. After a 15-minute exposure, the temperature of the dry sand had increased by ~40ºC. This is a dramatic change from the results obtained in the previous DRE Ottawa experiment where the temperature increased by ~75ºC within 2 minutes. Thus the use of dry sand poses a significant challenge to HPM neutralisation and the current experiment represent a worse case situation for the technique.

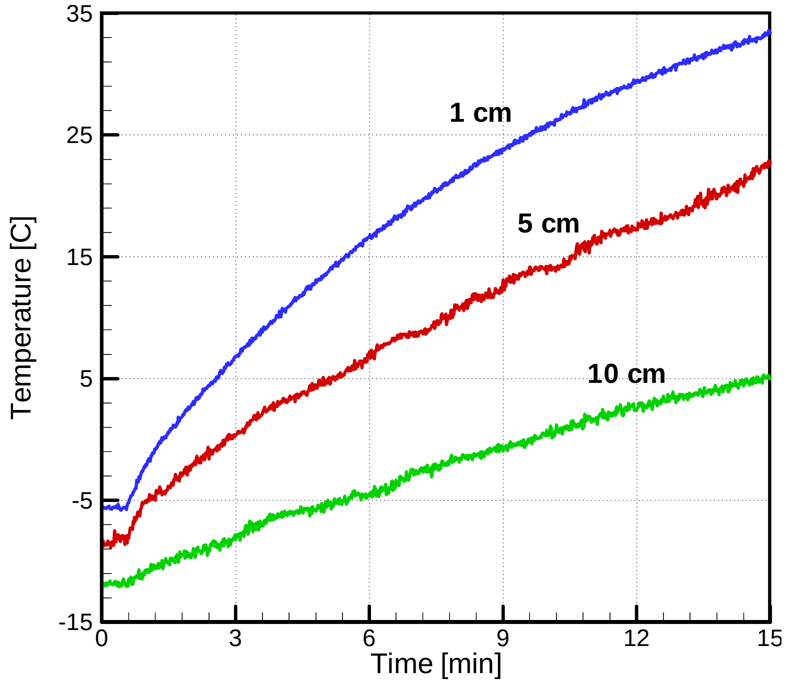

Figure 20. *Pre-test measurement of dry sand heating rate exposed to microwaves at 4.5 kW power.*

Another factor that affected temperature measurements is that the environmental conditions prevailing at the time of these tests were cold and windy. As a result, convection cooling was highly pronounced for these field trial measurements.

4.1.4 Power Density

No power densities or field distributions were measured during trials involving live explosives due to obvious dangers to personnel and equipment. It is assumed that the densities determined for the surrogate study apply to these experiments as well. These measured values indicate a Gaussian-like distribution of power with a peak power density of approximately 150 W/cm^2 that quickly drops to values of about 50 W/cm^2 approximately 2 cm from the waveguide central axis. See Section 3.2.3 for more detail.

4.1.5 Instrumentation

The results from these experiments consisted primarily of visual observations of the effect of HPM on actual landmine components. It was therefore imperative to have good video coverage to record the timing of events. Standard 8 mm video cameras were set on tripods for use at critical locations. In addition, a single high-speed digital video was positioned to capture the explosion of a landmine when it occurred.

The other important quantity to record was temperature. Several fibre optic thermometers (Photonetics MetriCor 2000) were used in the immediate vicinity of the landmines, as shown in Figure 21. Temperature values were recorded directly to a PC via a GPIB. Given the high likelihood of destroying the probes, a conscious decision was made to sacrifice the probes and to use them in an open-tip mode without the mechanical protection of quartz tube. This effectively provided real time measurements of temperature.

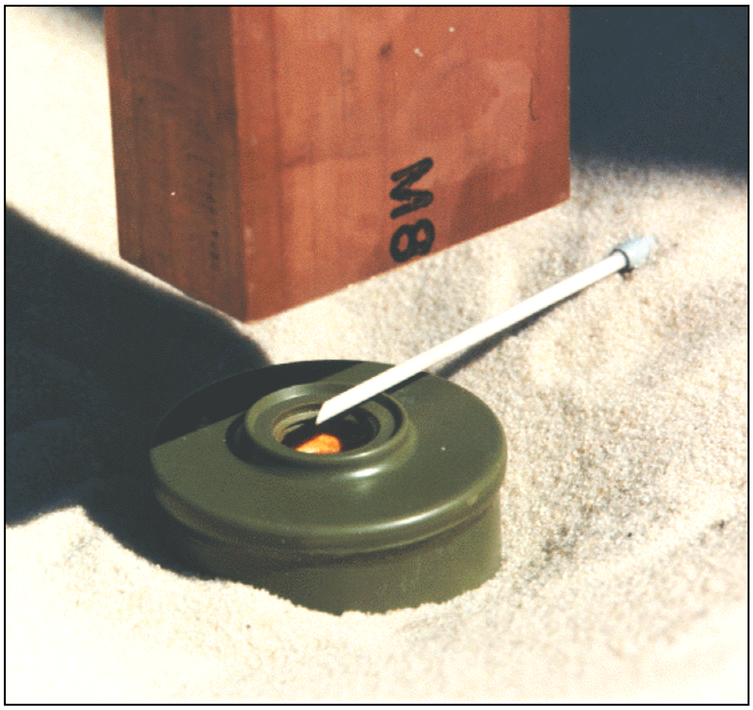

Figure 21. *Ceramic temperature probe located on top of PMA-2 mine body.*

4.2 Landmine Targets

The tests were carried out against the three types of AP landmines shown in Figure 22. These are the PMA-1, PMA-2 and PMA-3, respectively. These three landmines were chosen because they represent a real threat that is found in the field and they were available to this project. In addition, this selection of AP landmines offered several other advantages. They have different shape, the fuse position varies from one type to the next, and the fuses differ widely in their design, thus offering a good cross-section of targets. The general outer and explosive characteristics for these landmines are listed in Table 3.

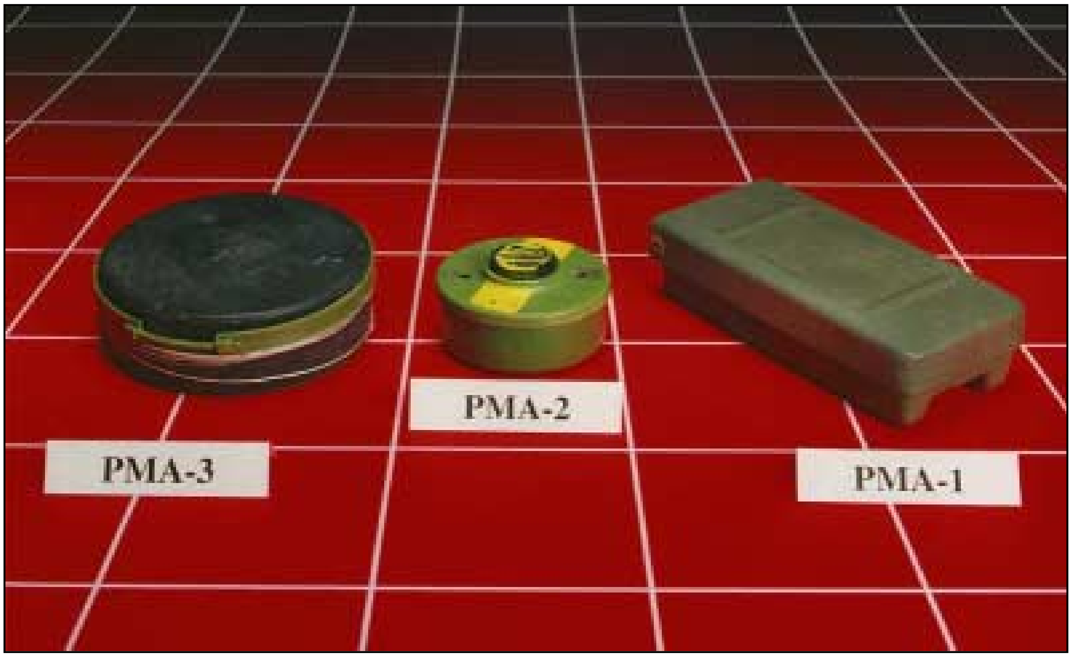

Figure 22. *Selection of landmines used for the HPM neutralisation feasibility trials.*

Table 3. *Main characteristics of the landmines used during these tests.*

NAME	SHAPE	EXPLOSIVE	MASS	HEIGHT	DIMENSIONS[1]
			gram	***mm***	***mm***
PMA-1	Rectangular	TNT	200	30	140 × 70
PMA-2	Circular	TNT	100	61	68
PMA-3	Circular	Tetryl	35	40	111

Note 1: Denotes the diameter for circular shapes and the plan view projection for the rectangular shape.

The former republic of Yugoslavia manufactured the three AP landmines selected for this study. They are all minimum metal landmines, meaning that they contain only a very small amount of metal, usually contained within the fuse, in order to minimise the probability of detection by standard mine detectors. The great majority of mine detectors deployed around the world operate on a metal detection principle. From the point of view of HPM neutralisation, it is important to consider the combination of geometrical and material characteristics of these landmines. The cross-section sketches displayed in Figure 23, Figure 24 and Figure 25 for the PMA-1, PMA-2 and PMA-3, respectively, provide some insight with respect to the physical characteristics of these landmines. There is often a lack of detailed information about the exact materials used in the construction of the mine bodies and fuse components, but the practical considerations stipulated earlier in this report about material selection probably hold true. The information presented below was obtained from reference [14] through collaboration with the mine manufacturer.

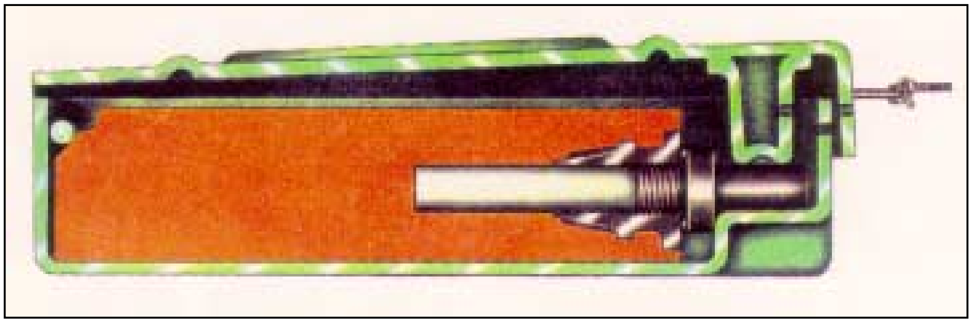

Figure 23. *Cross-section of the PMA-1 landmine.*

The PMA-1 consists of rectangular box with a hinged lid moulded from plastic. The end of the container is shaped like an anvil to receive the matching UPMAH-1 crusher fuse. The main charge is a block of cast TNT explosive inserted loosely within this box. The fuse is made of two separate components. The Bakelite crush tube is sealed at one end and contains a friction-sensitive compound that explodes when sufficient force is applied perpendicular to the thin wall. The other end accepts a standard No 8 detonator. The Bakelite fuse is attached to the TNT block via a threaded insert that is cast in the TNT. It is reported that there is a small rubber O-ring between the fuse and the threaded insert. The No 8 detonator consists of a thin aluminium hollow tube that contains a small amount of primary explosive at its sealed end. The other end, which is open, slides into the Bakelite component of the fuse. The operational position of the PMA-1 landmine placed the long axis of the detonator in a horizontal plane.

The cylindrical casing of the main body of the PMA-2 landmine is moulded from plastic. It is filled with cast TNT explosive, which constitutes the major portion of the main charge. There is a central fuse well on the upper surface of this landmine. A small pellet of RDX is located near the lower centre of the main charge to act as a booster. The UPMAH-2 fuse consists of three main components. The fuse body is made of hard plastic or Bakelite and is shaped to receive the plastic six-pronged plunger on its upper end. The pointed lower end of the plunger sits above a pellet of friction-sensitive compound that, itself, sits above a small detonator. The detonator assembly is bonded to the underside of the main fuse body. The only metal contained in this fuse is the thin aluminium shell of the detonator. As seen in Figure 24, the orientation of the long axis of the UPMAH-2 fuse in normally in the vertical direction.

The main body of the PMA-3 landmine is made of two large plastic parts shaped such that the upper portion is a rocker plate that is free to tip in any direction within the lower body. The two parts are held together solely by a large rubber cap that fits completely over the upper portion and down the side of the lower portion of the body. The upper body contains the main charge of Tetryl explosive within a small circular enclosure located on the geometrical centre of this landmine. The UPMAH-3 fuse fits in a threaded insert located at bottom dead centre of the landmine. It is constructed of plastic and there is a rubber O-ring between the fuse and the main body. The fuse contains a small steel needle potted in a friction-sensitive compound that is just below a detonator. The fuse is activated by the shearing action generated when the upper portion of the mine body is tilted relative to the lower portion. During normal operation of this landmine, the steel pin is in a vertical orientation.

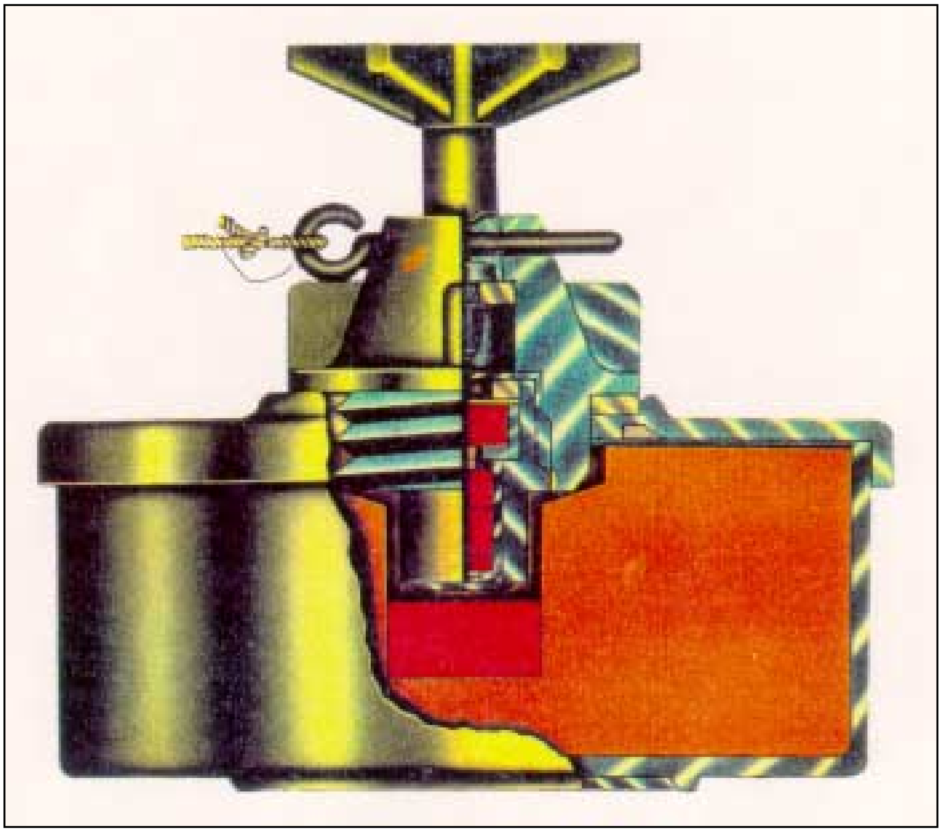

Figure 24. *Cross-section of the PMA-2 landmine.*

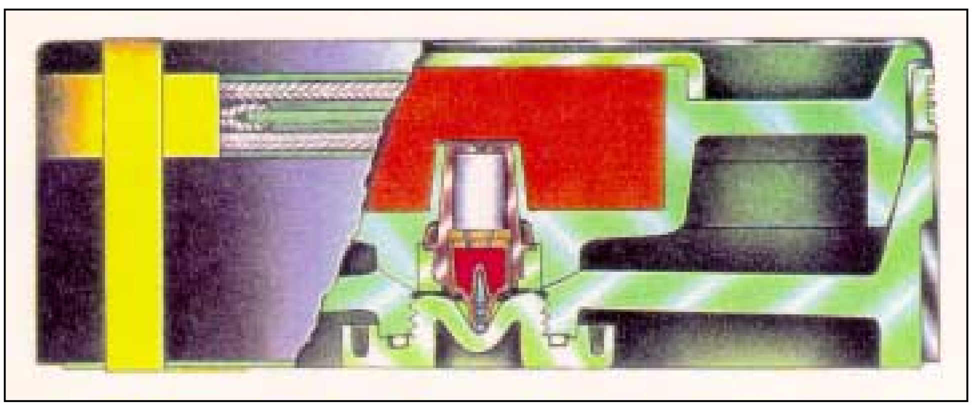

Figure 25. *Cross-section of the PMA-3 landmine.*

4.3 Practical Considerations and Problems

Section 3.3 described some of the problems encountered during the initial heating study at DRE Ottawa. Some of the solutions had to be further refined during the tests at DRE Suffield. There was also an additional problem due to poor power quality, as described below.

4.3.1 Power limitations

After setting up the magnetron at the trial location it was found that the unit could only be operated between 4 and 4.5 kW. Normal operation at DRE Ottawa (before and after the trial) was generally at 5kW. It is speculated that the main power feed was limiting the output power of the magnetron. This represented only a minor inconvenience that would only lower the heating rates but would not jeopardize the overall outcome of the tests. This problem should be rectified before future trials take place.

4.3.2 Smoke from mine

During the DRE Ottawa soil heating experiments, adding plastic Wrap with a 1 cm thick later of "blue" Styrofoam™ at the open end of waveguide, as shown in Figure 26 had rectified the problem with ingress of steam in the waveguide. This same solution was adopted for the DRE Suffield trials, but a detonator ignited during the first test without detonating the main charge of the landmine. The result was a breach of the seal at the end of the waveguide followed by ignition of the landmine body. A significant amount of smoke entered into the waveguide, thereby depositing carbon material on the Teflon plug, essentially creating a resistor across the interior of the waveguide. The waveguide temperature rose to the point were the solder on the flanges melted and the structure collapsed, as shown in Figure 27. Subsequent experiments had several Styrofoam™ plugs inserted at a variety of locations within the waveguide and no further difficulties were observed.

Figure 26. *Plastic Wrap and Styrofoam™ at the end of the waveguide over a PMA-2 landmine.*

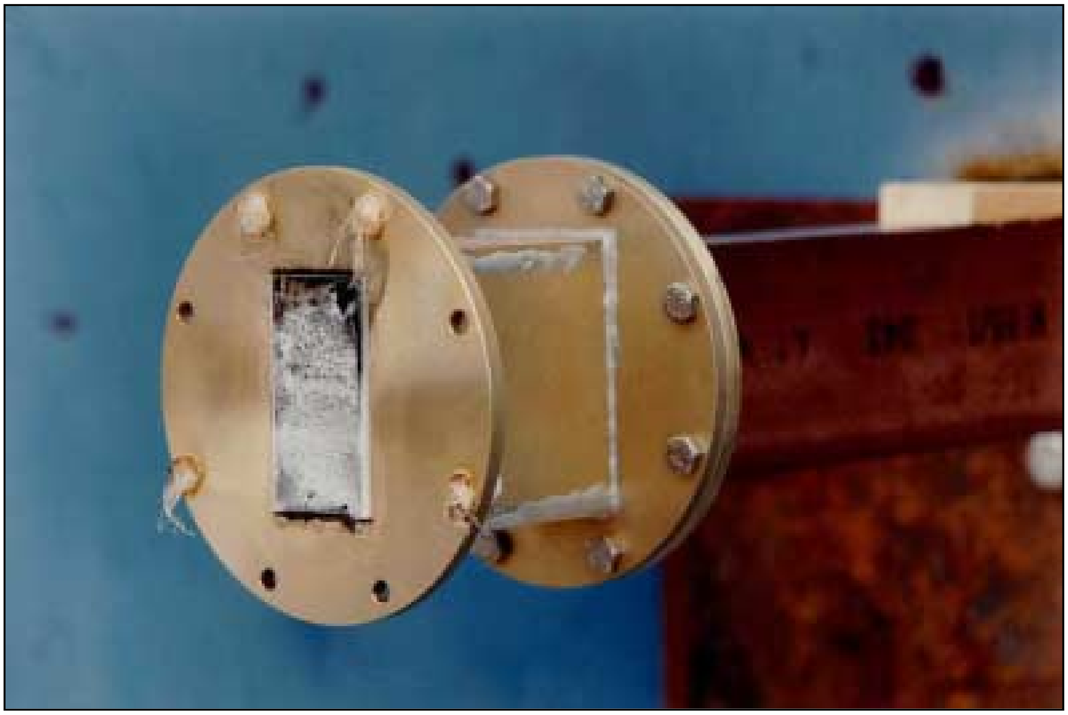

Figure 27. *Carbon deposit on plug created excessive heat build-up and structural collapse of waveguide.*

4.4 Test Results

A total of 12 HPM neutralisation tests were performed during this trial series. The first 10 tests were against landmine components that contained explosives. Of these tests, four were against fuses in isolation, two were against the main body of the landmine without a fuse, and the remainder were against complete landmine assemblies that were armed, as they would be found in an operational scenario. The last two HPM neutralisation tests were performed against a modern anti-tank landmine, the FFV-028, which contains an electronic fusing mechanism. The two FFV-028 landmines were inert, i.e., all explosive components had been removed, but the complete fuse was present.

The field trial reports for individual tests are presented in Annex A along with pictures of the setup and resulting damage to the landmines. This data is presented in the order that the tests were conducted. Within the present section, the data is regrouped according to trial target type, i.e., against fuses in isolation, against landmine bodies without a fuse, and against complete landmines.

4.4.1 Fuses in Isolation

The synopsis of the tests against fuses in isolation, given in Table 4, shows that all fuse types were neutralised. The timings were extracted from the video recordings while the damages are shown in the pictures of Annex A. Temperature was not recorded during these tests. The same fuse was used for the tests HPM-3A and HPM-3B.

The description of events within the result column is self explanatory, but the effect of fuse orientation during the HPM-3 test requires further discussion. The UPMAH-1 fuse is constructed of two parts that fit loosely into each other. The combination is screwed into the TNT explosive block to effectively bond the two parts. Since the TNT block was not used during these tests, the fuse components were free to move relative to each other. The test results show that heating of the long cylindrical metal tube is sensitive to orientation. When the fuse long axis was laid perpendicular to the electric field, it was not possible to damage the unit, even after 6 minutes of heating. However, when the long axis was rotated 90^{o} such that it was parallel to the field, the primer in the Bakelite portion of the fuse ignited within 19 seconds. Thus, the latter positioning optimized the coupling between the fuse and the electric field, while in the former this coupling was minimized. It is speculated that the metallic housing is acting as a dipole and, as such, preferentially coupling (and heating) when it is aligned with the field. If this is true, then the response of the mine may vary with the polarization of the incident beam. This requires further investigation.

Table 4. *Summary of results obtained against fuses in isolation.*

TRIAL #	TARGET	PLACEMENT	POWER	RESULT
			kW	
HPM-3A	UPMAH-1	Surface laid; ~50 mm below end of waveguide; perpendicular to E-field	4.2	No observable effect with up to 6:15 minutes of exposure [see note 1]
HPM-3B	UPMAH-1	Surface laid; ~50 mm below end of waveguide; parallel to E-field	4.2	T = 0:14 – smoke starts from fuse T = 0:19 – detonator is expelled from fuse head (crusher portion) [see note 1]
HPM-4	UPMAH-2	Surface laid; top of fuse ~10 mm below end of waveguide; vertical orientation	4.2	T = 0:45 – fuse plunger starts to melt T = 0:57 – smoke appears T = 1:15 – detonation of fuse
HPM-5	UPMAH-3	Surface laid; base of fuse ~50 mm below end of waveguide; vertical orientation	4.2	T = 5:22 – booster starts to boil out the top of the fuse

[Note 1]: Polarisation of the E-field appears to be important.

4.4.2 Landmine Bodies without Fuses

The synopsis of the tests against a PMA-1 and PMA-2 landmine body without a fuse is given in Table 5. For these tests, a single probe measured the heating rate in the vicinity of the landmine. The results are presented in Figure 28 and Figure 29 for the PMA-1 and PMA-2, respectively. In addition to temperature, these figures present a plot of the input power to the sample (i.e., the output from the magnetron) and the reflected power. The former value is an indication of duration of the microwave exposure. The latter measures reflections both; in the waveguide (due to obstructions, etc.), and also a fraction of the energy reflected from the soil surface. The fact that the reflected power is small with respect to the input power is the key observation from this data curve. The units on the plot are an indication of relative power. Absolute power levels are measured separately and are included in Table 4.

__Table 5.__ Summary of results obtained against landmine bodies in isolation.

TRIAL #	TARGET	PLACEMENT	POWER	RESULT
			kW	
HPM-6	PMA-2	Buried with top of body ~10 mm below end of waveguide	4.2	T = 5:37 – smoke starts, some sand slumps down over mine location T = 5:55 – smoke intensifies, further slumping of sand surface T = 7:50 – light steady smoke, slumping of sand continues T = 10:25 – HPM off
HPM-7	PMA-1	Buried with top of body ~10 mm below end of waveguide	4.2	T = 4:15 – slight slumping of sand starts T = 6:17 – smoke starts T = 7:05 – smoke intensifies T = 7:30 – large amount of black smoke emanates from ground T = 8:28 – flame appears, HPM off

The response for the PMA-1 body shows a steady rise in temperature over the first 3 minutes with an increase of the heating rate at about 3 minutes. The temperature continued to rise steadily until the 5-minute point. A plateau was then reached and smoke became visible soon thereafter. The plateau was maintained for a three-minute duration. At approximately 8 minutes after the start of the experiment, a very rapid rise in temperature occurred and flames became visible. The HPM power was turned off at that point and the fire consumed itself.

An examination of the remnants of the landmine body showed that the combustion was limited to the portion of the landmine that was located directly below the end of the waveguide, where HPM heating was maximised. The remainder of the landmine was relatively undamaged. It is speculated that extinction of the flame occurred as a result of the landmine being buried in sand, which quenched the inflow of fresh oxygen to continue the combustion process.

The response for the PMA-2 body shows a steady, but slow, rise in the temperature for the first 1 ¾ minute of heating, at which point the heating rate increases abruptly. The heating rate slowed down again after 4 minutes at which point slumping of the sand surface was observed, which suggests that a phase change was taking place in the landmine body, i.e., it was starting to melt. Small amounts of smoke started to be visible soon thereafter. The smoke intensified with time as exposure to the HPM energy continued. By roughly 8 minutes, open flame was visible.

Post-test examination of the damage to the PMA-2 landmine body revealed that it had opened up at some point during the test, allowing the explosive within to escape and filter through the adjacent sand. The liquefied explosive contaminated a significant amount of sand. The presence of smoke and flame also indicates that some of the material had been consumed through combustion.

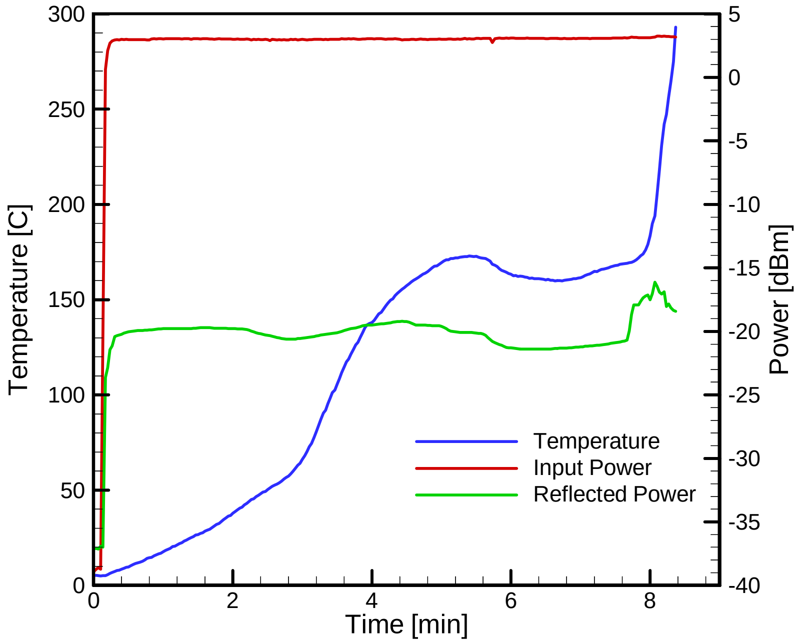

Figure 28. *Input and reflected HPM power with temperature history for PMA-1 body test (HPM-7).*

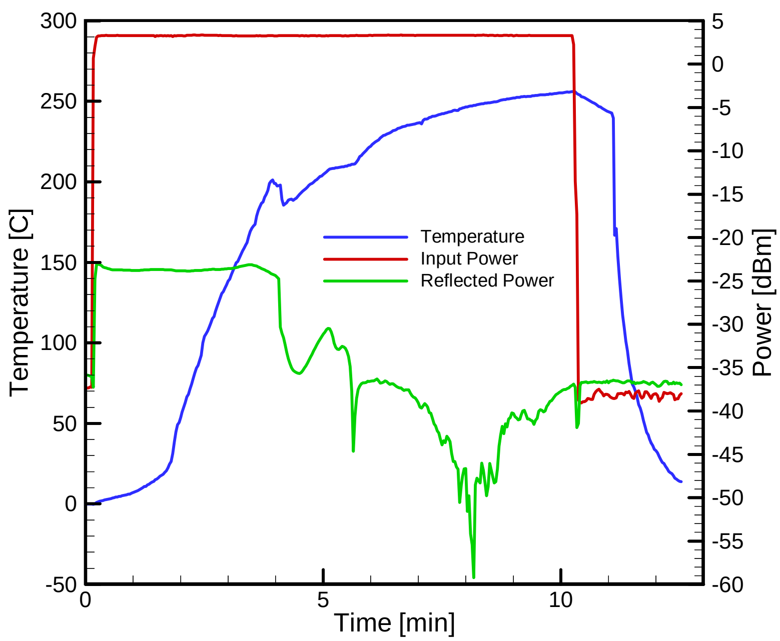

Figure 29. *Input and reflected HPM power with temperature history for PMA-2 body test (HPM-6).*

4.4.3 Fused and Armed Landmines

Four landmines were exposed to HPM radiation. Two tests resulted in high order detonation and two tests only initiated burning without detonation. Temperature was monitored for each test. Table 6 gives a synopsis of the results obtained for the four tests, which appeared to depend on the landmine type used, probably as a function of individual design.

The temperature response for the PMA-1 landmine is presented in Figure 30. A steady rise in temperature was recorded during the first two minutes of microwave exposure. At that point, the heating rate increased for 1 minute until high order detonation of the landmine occurred. Smoke became visible around 2:20 minutes, giving a first indication that the combustion process had started. The detonation resulted in extensive damage to the waveguide assembly, but fortunately, the protective measures employed worked and there was no damage to the magnetron and the waveguide assembly beyond the blast-resistant plug.

Two tests were carried out against PMA-2 landmines. Figures 31 and 32 show histories of the temperature and power for these tests. During the first test (HPM-1), there were difficulties with the temperature recording. The probe tip had been located to the side of the landmine body and it is likely that this measurement is that of soil heating. Furthermore, given that the probe was not directly in line with the central axis of the waveguide, it was in a location with reduced power density. Also, the landmine body would absorb and scatter the microwave energy. Thus, in retrospect, this particular location for measuring temperature was not ideal and subsequent measurements were done with the probe located above the landmines. The recording of incident and reflected HPM power was accurate.

The failure to properly capture temperature did not affect the success of the test. The effect of microwave heating was not immediately apparent with the exception of the occasional puff of

Table 6. *Summary of results obtained against complete landmines.*

TRIAL #	TARGET	PLACEMENT	POWER	RESULT
			KW	
HPM-9	PMA-1	Buried so that top of mine was ~10 mm below end of waveguide	4.2	T = 2:20 – smoke starts T = 2:55 – mine detonation
HPM-1	PMA-2	Buried so that top of fuse was ~10 mm below end of waveguide	4.5	T = 2:04 – fuse detonates without initiating the main charge; T = 3:12 – white-grey smoke appears T = 4:39 – waveguide fails due to melting of solder joint
HPM-8	PMA-2	Buried so that top of fuse was ~10 mm below end of waveguide	Variable	T = 0:00 – increase power set at 1 kW T = 1:00 – start increase power to 2 kW T = 2:00 – start increase power to 3 kW T = 2:19 – mine detonation as power just reached 3 kW
HPM-2	PMA-3	Buried so that top of mine was ~10 mm below end of waveguide	4.5	T = 1:06 – smoke appears T = 1:09 open flame is visible on top centre of mine, burning vigorously T = 1:48 flame dies out T = 1:53 – final pop, likely caused by fuse explosion

smoke and until just over 2 minutes after beginning the test. At that point, the fuse appears to have detonated, but without initiating the main charge. The resulting projectile tore through the plastic wrap at the end of the waveguide, allowing smoke to enter the waveguide to deposit on the surface of the Teflon blast plug. It is speculated that this formed an 'ad hoc' resistor. Local heating of the waveguide caused the solder on the flange and the plastic bolts to melt, resulting in structural failure of the waveguide assembly. Future runs replaced the plastic wrap with 2.5 cm foam plugs at multiple locations along the length of the waveguide. The foam plugs are electrically transparent but block smoke and small debris from entering the system. This problem did not reoccur for the remainder of the trial series.

A visual examination of the remnants of the mine body indicated that the mine was heavily deformed with separation of the upper portion of the landmine. It is speculated that the reason that the fuse failed to initiate the detonation of the main charge is that the fuse plunger mechanism was not mechanically held in place. Thus, when the primer within the fuse lit, it expelled the plunger before sufficient pressure and temperature could build up to continue the fuse train. This mechanism was also observed in a subsequent experiment (HPM-3) with the UPMAH-1 fuse in isolation. Proving this hypothesis would require further investigation that was beyond the scope of the present trials.

It is not clear from the result of this test what the exact mechanism was that led to initiation of the primer. It is speculated that simple dielectric heating was the main cause, but it is also possible that the initiation mechanism is a result of arcing within the fuse. This requires further investigation.

Because of the complications encountered with the initial PMA-2 test, a second test (HPM-8) was performed. Details of the power input and temperature curves are given in Figure 32. During the HPM-1 test, the magnetron was operated at 4.5 kW, but for this test it was decided to increase the power at set intervals. Thus, the power was to be set to 1kW for the first minute, 2kW for the second minute, etc. Shortly after the power was set to 3kW after approximately 2 minutes of irradiation, there was a high-order detonation of the landmine. This indicates that neutralization can be accomplished at lower power densities than those achieved at full power levels. The detonation destroyed the nearest portion of the waveguide, but the protection mechanisms beyond the blast plug performed well and the magnetron was not damaged.

Figure 32 indicates that the temperature had increased by only 9ºC at the time of detonation. This correlates well with the temperature increase registered in Figure 20 for sand in isolation. It is likely that improper contact between the tip of the temperature probe with the casing of the landmine was not achieved. Yet, the fact that detonation occurred is a good indication of the bulk heating characteristics of this HPM neutralisation technique.

Figure 33 shows the temperature response during the HPM-2 test with a PMA-3 landmine. A steady but slow rise in temperature is recorded in the first minute of microwave exposure. At that point, the heating rate increased dramatically, corresponding roughly with the appearance of open flame. Vigorous combustion continues for approximately 40 seconds, while the temperature exceeds the probe normal operating range. At 1:53 minute, detonation of the fuse was observed and microwave power was shut down soon after. Examination of the remnants of the landmine indicates that complete combustion of the explosive located in the top of the mine occurred before detonation of the fuse. This represents an ideal mine neutralisation result.

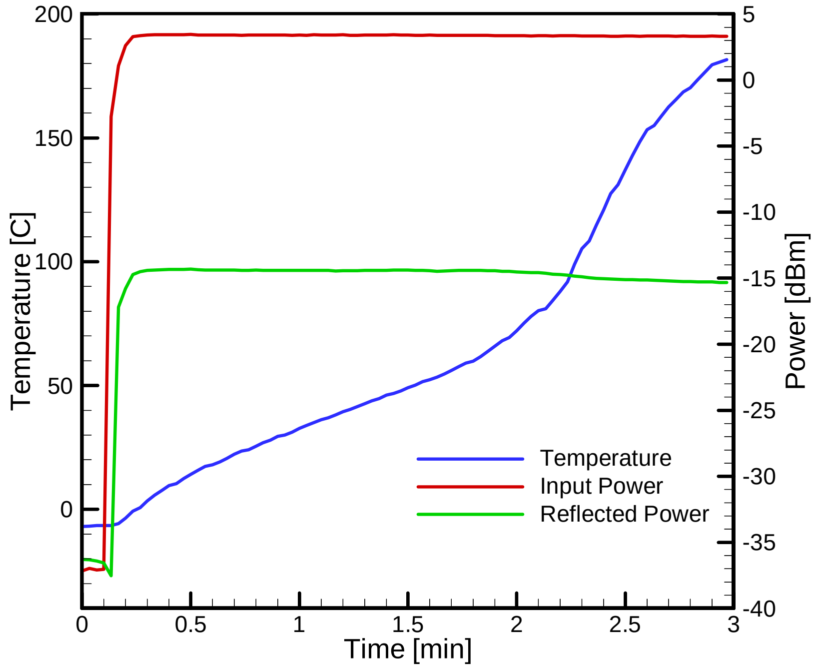

Figure 30. *Input and reflected HPM power with temperature history for PMA-1 mine test (HPM-9).*

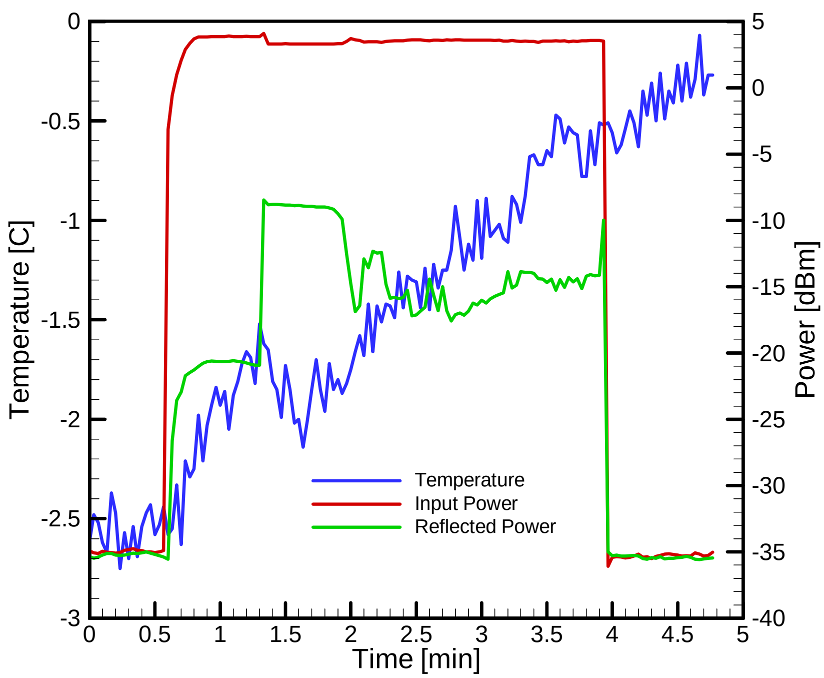

Figure 31. *Input and reflected HPM power with temperature history for PMA-2 mine test (HPM-1).*

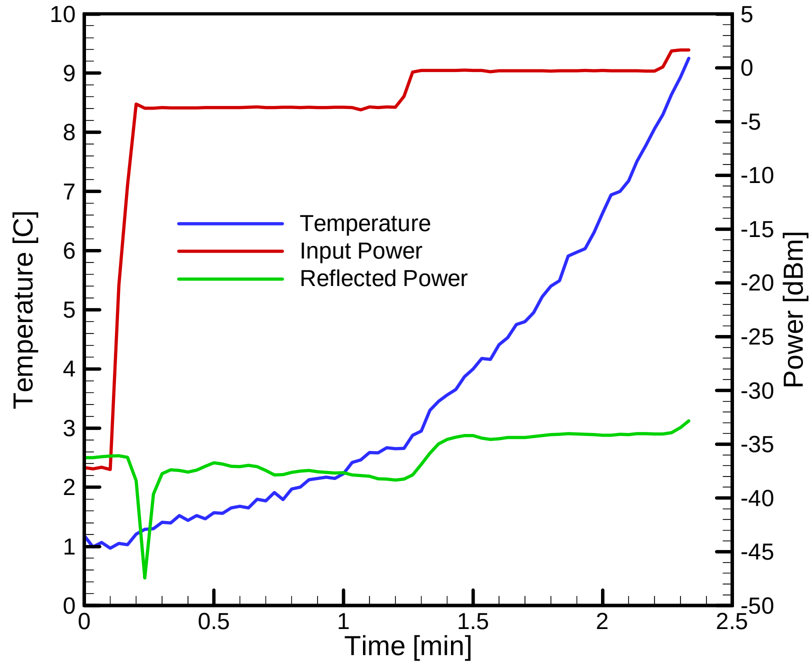

Figure 32. *Input and reflected HPM power with temperature history for PMA-2 mine test (HPM-8).*

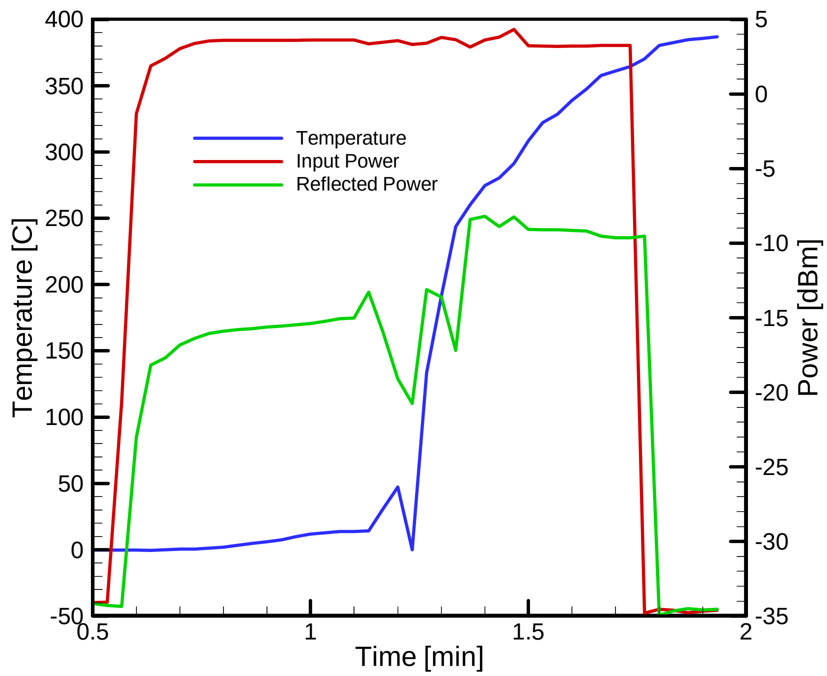

Figure 33. *Input and reflected HPM power with temperature history for PMA-3 mine test (HPM-2).*

4.5 Exposure of Electronic Landmines

The primary purpose of these trials was to expose anti-personnel landmines to the heating effects of HPM. Given that a system was available, there was also an opportunity to expose the electronic fuse of a modern landmine to HPM radiation to determine if it would result in damage. There had been reports that electronics could be disrupted or even damaged if exposed to a sufficiently strong microwave field. Thus, two FFV-028 landmines, as shown in Figure 34, were prepared for these trials. All explosives were removed, but the fusing system was otherwise fully operational.

Figure 34. *FFV-028 landmines without explosives but with fully operational electronic fuse.*

The construction of the FFV-028 gives it some HPM protection due to the metal casing, which unlike plastics and explosives, is not transparent to microwave radiation. It was however determined from a previous theoretical study [15] that microwave radiation could infiltrate the landmine body through seals and other small cracks. Figure 35 presents a cross section of the FFV-028. With the exception of the explosive fill, the majority of this device is constructed out of metallic materials. The fuse body is a machined block of metal that houses components such as a timer, a detonator, a fuse alignment mechanism and a spotting charge. Several wires are visible around this main block.

The setup for these tests is depicted in Figure 36. Instead of abruptly terminating the waveguide above the target, a standard gain horn antenna was attached to the end of the waveguide and offset from the soil surface by 300 mm. This reduced the power density impinging on the mine by approximately a factor of 20, but significantly increased the illuminated area and field uniformity. The two targets for these tests were used as is, hence they were not instrumented to monitor fuse functions during irradiation. This meant that the only way to determine if the fuse had been damaged was by functionality check before and after the tests. Following two exposure times of 30 and 300 seconds, respectively, it was determined that no changes to the mine electronics resulted from these tests. Thus, the only conclusion that can be drawn from this experiment is that there was no permanent damaged to the circuit components. Further experiments with significantly more power and proper instrumentation of the target would be required to determines if HPM is or is not effective to neutralise this class of landmines.

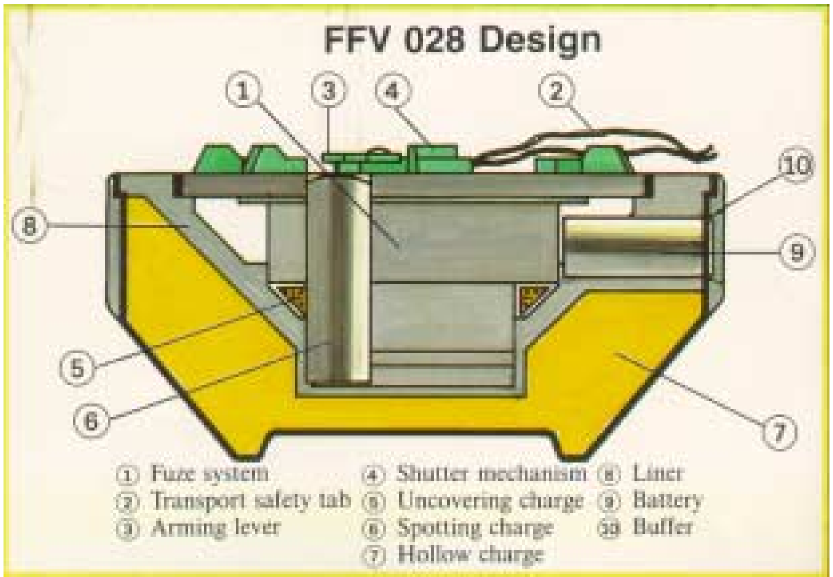

Figure 35. *Cross-section of the FFV-028 landmine showing various components.*

Figure 36. *Setup used to irradiate the FFV-028 landmines.*

5. Conclusions and Recommendations

In 1995, the DRDB initiated a project to assess if it was feasible to neutralise buried landmines using HPM energy. The concept of operation was for a neutralisation vehicle with this technology to treat small areas suspected of containing a landmine. These areas would be detected using a separate landmine detection vehicle. A series of preliminary experiments conducted in the DRE Ottawa laboratories demonstrated that significant heating rates could be imparted to soil using microwave power. It was also determined that soil dielectric constants, penetration depth and heating rates strongly depend on soil moisture content, with dry soil offering the best penetration.

Following these positive results, a decision was made to experiment with surrogate targets buried in soil and, if successful, to extend the experimentation to actual landmines. Thus, landmine surrogates were fabricated from various plastics. These were simple discs with dimensions similar to a typical anti-personnel landmine. Some of the discs were modified to emulate the gross configuration of the PMA-2 and PMA-3 landmines by adding a Bakelite disc or a rubber cap on the plastic discs. One interesting observation is the fact that although the Bakelite and rubber (both of which are strong microwave absorbers) influenced the top of the mine, the centre of the mine was not strongly influenced. It was speculated that this fact should not affect the applicability of the technique since HPM radiation would induce bulk heating of a minimum-metal landmine.

The results of the DRE Ottawa experiments showed that plastic surrogate landmines could be heated to well above their deformation temperature within a few minutes. This was true despite the fact that the plastics used were poor microwave absorbers. Many discs were in a gelatinous state when removed from the soil and could easily be crushed with a gloved hand. This indicated that significant deformation of the case of a plastic landmine could be expected, particularly if dissimilar materials with different absorption and thermal expansion rates were present. It was also reasonable to expect that the explosive content of a real landmine would heat in a similar fashion. The initiator and booster materials in the fuse would be particularly susceptible to such heating. Thus, based on the positive results from the DRE Ottawa experiments, it was decided to proceed with subjecting actual landmines to HPM heating.

Three minimum-metal landmines, the PMA-1, PMA-2 and PMA-3, were selected for feasibility trials at DRE Suffield. This selection offered targets of very different shapes and configurations. In addition to fully armed mines, testing was also performed on individual fuses and mine bodies in order to isolate the effects of microwaves on these components.

The tests against fuses in isolation demonstrated that fuse construction and orientation had a strong effect on the results. For the UPMAH-1 fuse, there was very strong polarization dependence with respect to the orientation of the incident electric field. When the fuse had maximum coupling to the electric field, it was initiated in 19 seconds. On the other hand, when the coupling was 90^{o} to this (i.e. minimum electric field coupling), it did not initiate over the course of 6 minutes of microwave exposure. Initiation of the UPMAH-2 fuse was achieved in 1:15 minute and that of the UPMAH-3 fuse in a little more than 5 minutes.

Two tests were performed against the PMA-1 and PMA-2 landmine body. In each case, melting and burning of the case and explosive was achieved 4 to 5 minutes of heating. It is suspected that this result is due to strong heating of the plastic cases since explosives are generally poor microwave absorbers.

Of the four tests carried out against fused and armed landmines, two resulted in high order detonations and two in burning that left the landmine effectively neutralised. The PMA-1 landmine, where the fuse had been oriented for maximum coupling, detonated after 2:55 minutes, while the PMA-2 detonated after 2:19 minutes. During another PMA-2 test, the fuse exploded but failed to initiate the main charge. Continued exposure of the disabled landmine initiated combustion of the plastic and explosive content. Finally, for the PMA-3, the explosive was fully consumed within 2 minutes and was followed shortly by the explosion of the fuse. This latter result is probably attributable to the configuration of this particular landmine where the main explosive charge is above the fuse.

Opportunity tests of a modern anti-tank landmine, the FFV-028, did not yield any conclusive results. Inspection of the electronic fuse functionality before and after the test did not reveal any permanent damage. However, the functionality of the electronic fuse during irradiation was not monitored.

It appears from the results of these experiments that HPM neutralisation of landmines is possible. These tests also opened a number of questions that should be answered to determine if HPM neutralisation technology is operationally practical and cost effective. In order to resolve these issues, it is recommended that the following course of action be taken:

- A standoff antenna should be designed and constructed for future trial work. This will allow the application of microwave energy from a distance and should result in a reusable applicator while reducing risk to personnel; and
- A study of the coupling of microwave energy to fuse components should be initiated. This would require the use of various blasting caps (as fuse surrogates) and actual antipersonnel and/or anti-tank mine fuses in order to establish the influence of fuse orientation and susceptibility to arcing and heating.

6. References

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Annex A: Field Trial Reports for Individual Shots

This Annex contains a summary of the 12 HPM neutralisation tests. The first 10 tests were either against landmine components or against fully assembled and armed landmines. The last two tests were performed against two inert (explosive fill removed) FFV-028 modern landmines that contain an electronic fuse. For each trial, a reproduction of the DRE Suffield trial datasheet is presented along with pictures giving some details about the test setup and the end result. The following table lists the tests conditions for each of the 12 datasets found in this Annex.

Trial #	Landmine	Configuration	Placement	Pages
HPM-1	PMA-2	Complete mine	Top of fuse ~10 mm below end of waveguide	
HPM-2	PMA-3	Complete mine	Top surface of mine ~20 mm below end of waveguide	
HPM-3A	PMA-1	Fuse only	On sand surface ~50 mm below end of waveguide; perpendicular to E-field	
HPM-3B	PMA-1	Fuse only	On sand surface ~50 mm below end of waveguide; parallel to E-field	
HPM-4	PMA-2	Fuse only	Top of fuse ~10 mm below end of waveguide	
HPM-5	PMA-3	Fuse only	Top of fuse ~40 mm below end of waveguide	
HPM-6	PMA-2	Body only	Top of body ~10 mm below end of waveguide	
HPM-7	PMA-1	Body only	Top of body ~10 mm below end of waveguide	
HPM-8	PMA-2	Complete mine	Top of mine fuse ~10 mm below end of waveguide	
HPM-9	PMA-1	Complete mine	Top of mine ~10 mm below end of waveguide	
HPM-10	FFV-028	Inert mine with fuse	Top of mine ~300 mm below end of horn	
HPM-11	FFV-028	Inert mine with fuse	Top of mine ~300 mm below end of horn	

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 09 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 065/97 **CROSS REF TO:** HPM-1

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF: E** 064 **N** 689

4. **SCHEDULED START TIME:** 13:00 **HRS** **ACTUAL START TIME:** 13:05 **HRS**

   ACTUAL ZERO TIME: 13:34 **HRS** **COMPLETION TIME:** 14:30 **HRS**

   REMARKS: There was a lot of site preparation to complete prior to trial zero time. Several systems were tested to make sure all was working as planned.

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. The splinter proof shelter was positioned under the surface of a plywood box filled with Mil Spec sand and a 1 cm gap was measured between the opening of the microwave tube and the mine fuse. This box was constructed with an open mesh bottom and was located in a wood runway to allow sand to escape into the hole. The runway ran over a hole to allow sand to escape into the hole. The runway terminated at a demolition area well away from the microwave tube so that if a demolition was required, damage to the test setup would be minimized. A winch cable was positioned up the length of the runway and attached to the box to enable it to be remotely winched over the hole to empty the sand and allow for recovery or winching to the disposal site. Prior to the trial on the mine, the ground was heated and three temperature probes measured results. The winch system was operated as well to ensure it was working correctly. The mine body was surface buried in a horizontal plane. The microwave energy was focussed directly onto the mine. The event was recovered on videotape and Scott had installed his high-speed digital video to record results as well. A temperature probe was placed on the mine to monitor temperatures the mine would see. The microwave system was controlled fro the bunker by DREO staff.

6. **RESULTS/COMMENTS:**
   The mine was exposed for about four minutes when the test was stopped as the microwave tube melted off at the Teflon bolts which connect the tube together. A 30-minute wait was observed and during this time, the mine was moved along the wood towing guide so that the sand would fall away. A video camera set at the sand disposal site showed the mine and fuse separated with the fuse completely melted. Personnel were allowed to view these components prior to demolition. ESEG personnel destroyed the mine body in situ. A piece of cellophane had been placed over the tube opening and it vaporised causing the inside of the tube to be coated with carbon, which caused the tube to overheat and melt the Teflon bolts.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-2 mines with fuse

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 37. *HPM-1 – PMA-2 mine with fuse located under waveguide.*

Figure 38. *HPM-1 – Damage to the mine assembly after heating and fuse separation.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 09 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 066/97 **CROSS REF TO:** HPM-2

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF:** **E** 064 **N** 689

4. **SCHEDULED START TIME:** 13:00 **HRS** **ACTUAL START TIME:** 13:05 **HRS**

   ACTUAL ZERO TIME: 14:45 **HRS** **COMPLETION TIME:** 15:30 **HRS**

   REMARKS: A new Microwave Tube was installed with three Styrofoam plugs inserted in it to prevent a similar incident as in trial one.

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. The Splinterproof shelter was positioned to protect the Microwave unit as in earlier preliminary trials. A PMA-3 Mine Fuzed was positioned under the surface of a plywood box filled with Mil Spec Sand and a 1 cm gap was measured between the opening of the Microwave Tube and the sand surface. There was a 1 cm cover of sand over the mine. This box was constructed with an open mesh bottom and was located in a wood runway which ran over a hole in the runway to allow sand to escape into the hole. The runway terminated at a demolition area well away from the Microwave Tube so that if demolition was required damage to the test setup would be minimized. A winch cable was positioned up the length of the runway and attached to the box to enable it to be remotely winched over the hole to empty the sand and allow for recovery or winching to disposal site. The mine body was surface buried in a horizontal plane. The Microwave energy was focussed directly onto the mine. The event was recorded on videotape and Scott had installed his High Speed Digital Video to record results as well. A temperature probe was placed on the mine to monitor temperatures the mine would see. The Microwave system was controlled from the bunker by DREO staff.

6. **RESULTS/COMMENTS:**
   The mine was exposed for the required time and flames were seen during the exposure. As well a pop was heard which may have been the fuse exploding. The Microwave Tube remained intact. A 30 minute wait was observed and during this time the mine was moved along the wood towing guide so that the sand would fall away. A video camera set at the sand disposal site showed the mine was burned on the plastic case. Personnel were allowed to view these components prior to demolition of them. The mine was destroyed in situ.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-3 mine with fuse

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 39. *HPM-2 – PMA-3 located under end of waveguide before burial.*

Figure 40. *HPM-2 – Damage to PMA-3 after heating ignited explosive located near top of mine.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 10 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 067/97 **CROSS REF TO:** HPM-3

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF: E** 064 **N** 689

4. **SCHEDULED START TIME:** 09:00 **HRS** **ACTUAL START TIME:** 09:00 **HRS**

   ACTUAL ZERO TIME: 10:10 **HRS** **COMPLETION TIME:** 10:40 **HRS**

   REMARKS:

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. A PMA-1 Fuze w/Igniter was positioned on the surface of a box filled with Mil Spec Sand with the box positioned under the business end of the microwave equipment. The fuze was positioned laying horizontal and so that there was a 5 cm standoff between the fuze and metal tube port channelling the energy at the target fuze. Remotely from the cover of an on-site protective bunker, the fuze was subjected to the energy source for approximately 6 min with no obvious reaction. Power was discontinued, a 30 min safety wait was employed then the fuze was reoriented under the energy tube port, once again at a 5 cm standoff. Power was remotely applied and the fuze was subjected to the energy source for approximately 1 min when the igniter functioned causing the ejection of the still live detonator out of the igniter. Power discontinued and once again a 30 min safety wait was employed prior to approaching the ground zero site. Trial observed and recorded using high speed and video coverage.

6. **RESULTS/COMMENTS:**
   Good trial although a detonation of the complete fuzing system was hoped for. Live fuze components were recovered and retained by ESEG personnel for disposal at trial completion. All scientific data and trial results were recorded by trial director and his scientific staff.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-1 Fuze w/Igniter

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 41. *HPM-3 – PMA-1 fuse located perpendicular to electric field on top of soil.*

Figure 42. *HPM-3 – Heating ignited primer in crusher part, expelling the detonator (right).*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 10 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 068/97 **CROSS REF TO:** HPM-4

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF: E** 064 **N** 689

4. **SCHEDULED START TIME:** N/A **HRS** **ACTUAL START TIME:** 10:40 **HRS**

   ACTUAL ZERO TIME: 10:53 **HRS** **COMPLETION TIME:** 11:00 **HRS**

   REMARKS:

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. A PMA-2 Fuze w/Igniter was positioned vertically and partially buried at the surface of a box filled with Mil Spec Sand with the box positioned under the business end of the microwave equipment. The fuze was positioned standing vertically, detonator end buried in the sand so that there was a 1 cm standoff between the top of the fuze and the metal tube port channelling the energy at the target fuze. Remotely from the cover of an on-site protective bunker, the fuze was subjected to an energy source for approximately 2 minutes when the primer functioned but with no detonation of the main detonator charge. Trial observed and recorded using on-site high speed and video coverage.

6. **RESULTS/COMMENTS:**
   Good trial although a detonation of the complete fuzing system was hoped for. Live fuze components were recovered and retained by ESEG personnel for disposal at trial completion. All scientific data and trial results were recorded by trial director and his scientific staff.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-2 Fuze w/igniter

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 43. *HPM-4 – PMA-2 fuse located flush to sand below end of waveguide.*

Figure 44. *HPM-4 – Damaged PMA-2 fuse after heating ignited primer but not detonator.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 10 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 069/97 **CROSS REF TO:** HPM-5

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF:** **E** 064 **N** 689

4. **SCHEDULED START TIME:** N/A **HRS** **ACTUAL START TIME:** 11:00 **HRS**

   ACTUAL ZERO TIME: 11:28 **HRS** **COMPLETION TIME:** 11:33 **HRS**

   REMARKS:

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. A PMA-3 Fuze w/Igniter was positioned vertically on the surface of a box filled with Mil Spec Sand with the box positioned under the business end of the microwave equipment. The fuze was positioned standing vertically, detonator end up so top of fuze rested on the sand surface so that there was a 5 cm standoff between the top of the fuze (sand surface) and the metal tube port channelling the energy at the target fuze. The fuze was subjected to energy source for approximately 5 minutes when the complete fuze functioned.

6. **RESULTS/COMMENTS:**
   Good trial and a total detonation of the complete fuzing system was achieved. All scientific data and trial results were recorded by trial director and his scientific staff.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-3 Fuze w/igniter

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 45. *HPM-5 – PMA-3 fuse located on sand below end of waveguide.*

Figure 46. *HPM-5 – Damage to the PMA-3 fuse after exposure to HPM heating.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 10 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 070/97 **CROSS REF TO:** HPM-6

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF:** **E** 064 **N** 689

4. **SCHEDULED START TIME:** N/A **HRS** **ACTUAL START TIME:** 12:30 **HRS**

   ACTUAL ZERO TIME: 12:58 **HRS** **COMPLETION TIME:** 13:05 **HRS**

   REMARKS:

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. A PMA-2 Mine w/o Fuze was positioned on the surface of a box filled with Mil Spec Sand with the box positioned under the business end of the microwave equipment. This box was constructed with an open mesh bottom and was located in a wooden runway which led over a hole in the runway to allow sand to escape into the hole. The runway continued on to a demolition area as required. A winch cable was positioned up the length of the runway and attached to the box to enable it to be remotely winched over the hole to empty the sand and allow for recovery or winching to disposal site. The mine body was surface buried in a horizontal plane so that there was a 4 cm distance between bottom of mine and the metal tube port channelling the energy at the target fuze which gave a 1 cm standoff between top of mine and metal tube. Remotely from the on site blast shelter, the mine was subjected to an energy source for approximately 11 minutes. There was no detonation of mine but the energy application caused the mine to melt and burst into flames. Power was discontinued and the box and mine were remotely winched down the runway, over the hold, sand removed and mine viewed in location by video set-up. A 30 min safety wait was employed prior to approaching ground zero and then any remaining live mine components/filling were removed awaiting demolition by ESEG personnel.

6. **RESULTS/COMMENTS:**
   Good trial although no detonation of the complete mine was achieved. Live filling/components recovered and retained by ESEG personnel for disposal at trial completion. All scientific data and trial results were recorded by trial director and his scientific staff.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-2 w/o fuze

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 47. *PMA-2 mine body being located before burial. Note temperature probe above.*

Figure 48. *Damaged PMA-2 mine body after HPM heating. Part on left is matrix of sand/explosive.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 10 Apr 97

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 071/97 **CROSS REF TO:** HPM-7

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF: E** 064 **N** 689

4. **SCHEDULED START TIME:** N/A **HRS** **ACTUAL START TIME:** 13:05 **HRS**

   ACTUAL ZERO TIME: 14:09 **HRS** **COMPLETION TIME:** 14:45 **HRS**

   REMARKS:

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. A PMA-1 Mine w/o Fuze was positioned on the surface of a box filled with Mil Spec Sand with the box positioned under the business end of the microwave equipment. This box was constructed with an open mesh bottom and was located in a wooden runway which led over a hole in the runway to allow sand to escape into the hole. The runway continued on to a demolition areas as required. A winch cable was positioned up the length of the runway and attached to the box to enable it to be remotely winched over the hole to empty the sand and allow for recovery or winching to disposal site. The mine body was surface buried in a horizontal plane so that there was a 5.7 cm distance between bottom of mine and the metal tube port channelling the energy at the target fuze which gave a 1 cm standoff between top of mine and metal tube. Remotely from on site blast shelter, the mine was subjected to an energy source for approximately 11 minutes. There was no detonation of mine but the energy application caused the mine to melt and burst into flames. Power was discontinued and the box and mine were remotely winched down the runway, over the hole, sand removed and mine viewed in location. A 30 min safety wait was employed prior to approaching ground zero and then any remaining live mine components/filling were removed awaiting demolition by ESEG personnel.

6. **RESULTS/COMMENTS:**
   Good trial although no detonation of the complete mine was achieved. Live filling/components recovered and retained by ESEG personnel for disposal at trial completion. All scientific data and trial results were recorded by trial director and his scientific staff.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-1 w/o fuze

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 49. *PMA-1 mine body with explosive block being located under end of waveguide.*

Figure 50. *Damage to PMA-1 mine body after exposure to HPM heating.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 10 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 072/97 **CROSS REF TO:** HPM-8

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF: E** 064 **N** 689

4. **SCHEDULED START TIME:** N/A **HRS** **ACTUAL START TIME:** 14:45 **HRS**

   ACTUAL ZERO TIME: 15:20 **HRS** **COMPLETION TIME:** 16:00 **HRS**

   REMARKS:

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. A PMA-2 Mine with Fuze was positioned on the surface of a box filled with Mil Spec Sand with the box positioned under the business end of the microwave equipment. This box was constructed with an open mesh bottom and was located in a wooden runway, which led over a hole in the runway to allow sand to escape into the hole. The runway continued on to a demolition area as required. A winch cable was positioned up the length of the runway and attached to the box to enable it to be remotely winched over the hole to empty the sand and allow for recovery or winching to disposal site. The mine body was surface positioned in a horizontal plane so that there was a 1 cm standoff distance between top of mine fuze and the metal tube port channelling the energy at the target fuzed mine. The mine was remotely subjected to an energy source for approximately 2 min from the cover of the on site protective bunker. The mine detonated from the energy source application. High speed camera and video coverage recorded trial operations.

6. **RESULTS/COMMENTS:**
   Good trial. Detonation of the complete mine was achieved. All scientific data and trial results were recorded by trial director and his scientific staff.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-2 Mine with fuze

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 51. *High-speed video frames showing detonation of PMA-2 landmine due to HPM heating.*

Figure 52. *Damage to experimental setup following detonation of PMA-2 landmine.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 11 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 073/97 **CROSS REF TO:** HPM-9

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF:** **E** 064 **N** 689

4. **SCHEDULED START TIME:** 09:00 **HRS** **ACTUAL START TIME:** 09:15 **HRS**

   ACTUAL ZERO TIME: 09:58 **HRS** **COMPLETION TIME:** 12:00 **HRS**

   REMARKS:
   The new Microwave Tube remained installed with three styrofoam plugs inserted in it to prevent a similar incident as in trial one.

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. The Splinterproof shelter was positioned to protect the Microwave unit as in earlier preliminary trials. A PMA-1 Mine Fuzed was positioned 2 cm under the surface of a plywood box filled with Mil Spec Sand and a 1 cm gap was measured between the opening of the Microwave Tube and the sand surface. There was a 1 cm cover of sand over the mine. This box was constructed with an open mesh bottom and was located in a wood runway which ran over a hole in the runway to allow sand to escape into the hole. The runway terminated at a demolition area well away from the Microwave Tube so that it a demolition was required damage to the test setup would be minimized. A winch cable was positioned up the length of the runway and attached to the box to enable it to be remotely winched over the hole to empty the sand and allow for recovery or winching to disposal site. The mine body was surface buried in a horizontal plane. The Microwave energy was focussed directly onto the mine. The event was recorded on videotape and Scott had installed his High Speed Digital Video to record results as well. A temperature probe was placed on the mine to monitor temperatures the mine would see. The Microwave system was controlled from the bunker by DREO staff.

6. **RESULTS/COMMENTS:**
   The mine was exposed and detonated at 09:58 hrs. The Microwave tube was completely blown off and no damage to the Magnetron occurred. Scott recorded the detonation with his High Speed Video.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** PMA-1 Mine Fuzed

NOTE: This is a reproduction of the original report combined with the munitions list.

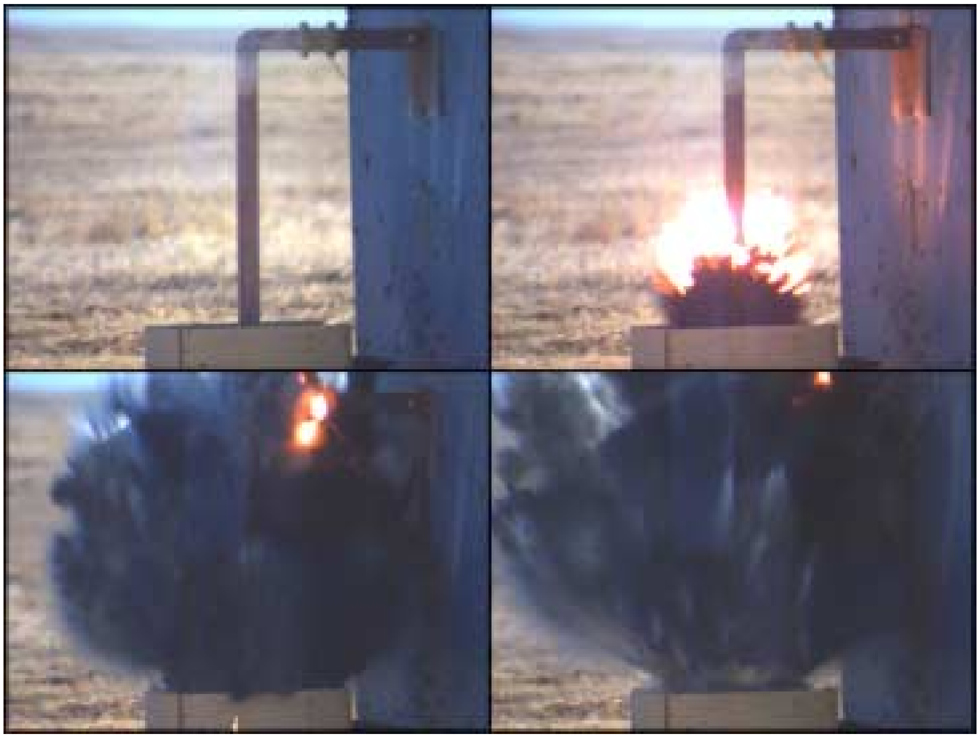

Figure 53. *High-speed video frames showing detonation of PMA-1 landmine due to HPM heating.*

Figure 54. *Damage to experimental setup following detonation of PMA-1 landmine.*

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 11 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 074/97 **CROSS REF TO:** HPM-10

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF:** **E** 064 **N** 689

4. **SCHEDULED START TIME:** 09:00 **HRS** **ACTUAL START TIME:** 09:15 **HRS**

   ACTUAL ZERO TIME: 10:48 **HRS** **COMPLETION TIME:** 11:30 **HRS**

   REMARKS:
   A new Microwave Tube was attached and it had a flared opening.

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. The Splinterproof shelter was positioned to protect the Microwave unit as in previous trials. An FFV Mine w/o fuze was buried in top soil and a 30 cm air gap between the mine and the opening of the flared tube head was established. The mine battery retaining cap was drilled with a 1/8″ hole so as to vent should the lithium battery rupture, due to heat build-up during exposure. There were no temperature probes used on this trial. The length of exposure would be 30 seconds for the initial test. As this mine was not fuzed and only the electronics were being tested for damage the remote mine removal system was not required. The even was viewed using video camera and monitors.

6. **RESULTS/COMMENTS:**
   The mine was exposed for 30 seconds and after a waiting period, was approached and the mine was carefully removed by ESEG personnel. There was no apparent damage to the mine or battery, however, further testing of the electronics systems might prove otherwise. ESEG personnel removed the mine from the test site.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** FFV Mine w/o fuze

NOTE: This is a reproduction of the original report combined with the munitions list.

DRES TECHNICAL SERVICES FIELD TRIAL REPORT

Date of Trial: 11 April, 1997

1. **FTP No.** 270 – Mine Countermeasures HPM Trials

2. **TECH SVCS TRIAL No.:** 075/97 **CROSS REF TO:** HPM-11

3. **TRIAL LOCATION:** HOB EAST MINE SITE **GRID REF: E** 064 **N** 689

4. **SCHEDULED START TIME:** 09:00 **HRS** **ACTUAL START TIME:** 09:15 **HRS**

   ACTUAL ZERO TIME: 11:14 **HRS** **COMPLETION TIME:** 11:30 **HRS**

   REMARKS:
   A new Microwave Tube was attached and it had a flared opening.

5. **SETUP/DATA/EVENTS:**
   The HPM Microwave equipment and trailer were deployed by DRES and visiting DREO personnel at the HOB East Mine Site. The Splinterproof shelter was positioned to protect the Microwave unit as in previous trials. A new FFV Mine which was not fuzed was buried in top soil and a 30 cm air gap between the mine and the opening of the flared tube head was established. The mine battery retaining cap was drilled with a 1/8″ hole so as to vent, should the lithium battery rupture due to heat build up during exposure. There was one temperature probe used on this trial and it was placed on top of the mine body. The length of exposure would be five minutes. As this mine was not fused and only the electronics were being tested for damage the remote mine removal system was not required. The event was viewed using Video camera and monitors.

6. **RESULTS/COMMENTS:**
   The mine was exposed for five minutes and during the exposure, steam was seen coming from the soil due to heat build up. After the exposure, a 30 minute wait was observed so that the mine could cool off. The mine was carefully removed by ESEG personnel and again, no visible damage was seen. Further electronic tests will confirm any internal damage. The mine was removed by ESEG personnel.

7. **MUNITIONS EXPENDED FOR THIS TRIAL:** FFV Mine w/o fuze

NOTE: This is a reproduction of the original report combined with the munitions list.

Figure 55. *FFV-028 landmine being prepared for exposure of its electronics to HPM radiation.*

Figure 56. *FFV-028 mine covered with soil for exposure to HPM irradiation.*

List of symbols/abbreviations/acronyms/initialisms

AP	Anti-Personnel
CRD	Centre de recherche pour la défense
DND	Department of National Defence
DRDB	Defence Research and Development Branch
DRDD	Direction pour la recherche et le développement pour la défense
DRE	Defence Research Establishment
FFV-028	Designation of an anti-tank landmine with electronic fuse, from Sweden
GPIB	General Purpose Interface Bus
HPM	High Power Microwaves
ILDP	Improved Landmine Detection Project
ILDS	Improved Landmine Detection System
IR	Infra-Red
M14	Designation for an anti-personnel landmine of US origin
MHP	Micro-ondes de haute puissance
PC	Personal Computer
PMA-1/2/3	Designation of anti-personnel landmines from Yugoslav origin
PMN	Designation of an anti-personnel landmine of Russian origin
RDX	Cyclotrimethylenetrinitramine, high explosive
TNT	Trinitrotoluene, high explosive
UPMAH-1/2/3	Designation of the fuse for the PMA-1/2/3 landmines
VS-50	Designation for an anti-personnel landmine of Italian origin