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Experimental Assessment of Two Exothermic Systems to Neutralize Landmines

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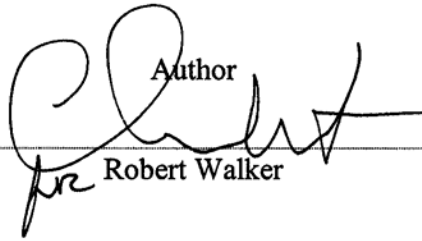
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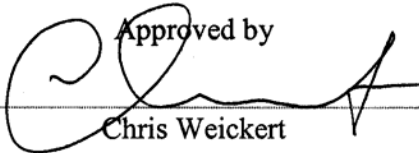
Defence R&D Canada – Suffield

Technical Report

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Abstract

During the late 1990s, Defence Research and Development Canada – Suffield investigated a variety of principles and techniques to neutralize land mines, including the use of exothermic reactions aimed at burning the land mines, as opposed to detonating them. During a six-week period ending in June 1998, trials were conducted with two thermite-based mine/unexploded ordnance (UXO) destruction systems, one marketed by CIL/Evan and one by Dew Engineering. All mines tested were partially or fully exposed. Both thermite systems caused most metallic mines to detonate after variable periods of burning. Thermite was generally more effective against mines with a smaller amount of explosive (anti-personnel (AP) mines) and mines with Bakelite or plastic casing materials. The CIL/Evan product, being a loose powder, was more adaptable to unusual surface contours. The solid DEW unit was less suitable for surfaces that were uneven or not level. Both systems are considered non-explosive and non-flammable by current transport and storage safety regulations. Their unit costs are comparable to military pattern explosives. This study indicates that thermite might be applicable in limited circumstances only—perhaps where the mines are exposed or removed, unfused, and when disposal explosives are unavailable or difficult to obtain.

Résumé

À la fin des années 1990, Recherche et développement pour la défense Canada – Suffield a étudié une variété de principes et de techniques visant à neutraliser les mines terrestres comprenant l'utilisation de réactions exothermiques destinées à brûler les mines terrestres au lieu de les détoner. Des essais ont été conduits durant une période de six semaines jusqu'en juin 1998, avec deux systèmes de destruction de munitions explosives non explosées (UXO) / mines à base de thermite, l'un commercialisé par CIL/Evan et l'autre par Dew Engineering. Toutes les mines testées étaient partiellement ou complètement exposées. Les deux systèmes thermites ont fait détoner la plupart des mines métalliques après des périodes variables de combustion. La thermite était généralement moins efficace contre les mines ayant une quantité d'explosif moindre (mines antipersonnel) et les mines ayant de la bakélite ou des matériaux à enveloppes en plastique. Le produit de CIL/Evan, étant composé d'une poudre non comprimée, était plus adaptable à des contours de surfaces inhabituelles. L'unité solide DEW était moins adaptée aux surfaces irrégulières et non nivelées. Les deux systèmes sont considérés comme non explosifs et non inflammables par les règlements actuels de la sécurité du transport et du stockage. Leur coût à l'unité est comparable à celui des explosifs de type militaire. Cette étude indique que la thermite ne pourrait être applicable que dans certaines circonstances seulement – peut-être quand les mines sont exposées, enlevées ou désamorçées ou bien encore quand des explosifs d'élimination ne sont pas disponibles ou sont difficiles à obtenir.

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Executive summary

Defence Research and Development Canada (DRDC) Suffield conducted trials of two thermite-based mine/ unexploded ordnance (UXO) destruction systems during the period 20 May - 30 June 1998. The two systems, one marketed by CIL/Evan and one by DEW Engineering, were tested against buried anti-tank (AT) and anti-personnel (AP) mines. Mines tested had metal, plastic or Bakelite casings and all mines had their upper or side surfaces exposed for better thermal contact.

Thermite is a mixture of powdered or granular aluminum metal and powdered iron oxide. It has an ignition temperature of over 500°C and a burning temperature of about 2500°C. At full burn, the iron oxide melts and flows. The resultant molten slug burns through the casing of a mine/UXO and ignites the explosive contents. The concept is to apply the thermite in a manner that allows it to melt through the mine casing and cause the explosive to burn out without initiating the fuse.

With one exception, all thermite systems evaluated caused exposed mines to either burn out or detonate. The risk of damage to surrounding infrastructure and terrain from fire from molten fragments of a detonating metal mine is high, requiring that the thermite charge be used in a safe area, such as a demolition pit or quarry. The success rates in the trials show a promising trend for the use of thermite against AP blast and plastic-cased AT mines. However, the method of delivering the heat to the mine, either using heat conduction or heat convection principles, has a strong influence on the effectiveness of the neutralization system. When applied to specific areas on a mine, commercially available thermal neutralization products, such as Thiokol Humanitarian Demining Flare and DERA *FireAnt*, may be more effective than bulk thermite at penetrating the mine case. These products provide a highly directional flame giving more consistent results than the thermite products investigated in the current study.

Thermite is not an explosive and is therefore easier and less restrictive to transport, store and handle for field use. At present, thermite may be useful in normal humanitarian demining operations, and in the destruction of individual mines or stockpiled mines/UXO. Ensuring that the latter are unfused would greatly reduce the probability of detonation.

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Sommaire

Recherche et développement pour la défense Canada (RDDC) Suffield a conduit des essais sur deux systèmes de destruction de munitions explosives non explosées /mines à base de thermité, durant une période allant du 20 mai au 30 juin 1998. Les deux systèmes, l'un commercialisé par CIL/Evan et l'autre par DEW Engineering ont été testés contre des mines antichar (AC) et antipersonnel (AP). Les mines testées avaient des enveloppes en métal, bakélite ou plastique et toutes les mines avaient leurs surfaces supérieures ou latérales exposées pour obtenir un meilleur contact thermique.

La thermité est un mélange d'aluminium en poudre ou granuleux et d'oxyde de fer en poudre. Sa température d'allumage est supérieure à 500°C et sa température de combustion est de 2500°C environ. Quand il est complètement enflammé, l'oxyde de fer fond et coule. La balle fondue qui en résulte brûle à travers l'enveloppe de la mine/UXO et enflamme les contenus explosifs. Le concept consiste à appliquer la thermique de manière à lui permettre de fondre à travers l'enveloppe de la mine et de causer la combustion de l'explosif sans toutefois déclencher l'amorce.

Tous les systèmes de thermité évalués, avec une exception, ont fait soit brûler soit détoner les mines exposées. Les risques de causer des dommages à l'infrastructure environnante et au terrain avec le feu provenant des fragments fondus d'une mine métallique qui détone sont hauts, ce qui exige que la charge thermité soit utilisée dans une zone sécuritaire telle qu'un chantier de démolition ou une carrière. Les taux de succès des essais indiquent une tendance prometteuse en ce qui concerne l'utilisation de la thermité contre les explosions AP et les mines AC ayant des enveloppes en plastique. La méthode de chauffage de la mine qui utilise soit la conduction de la chaleur ou les principes de la convection de la chaleur a cependant une grande influence sur l'efficacité du système de neutralisation. Quand on les applique à des parties spécifiques sur une mine, les produits de neutralisation thermique disponibles dans le commerce, tels que Thiokol Humanitarian Demining Flare and DERA FireAnt, peuvent être plus efficaces à pénétrer l'enveloppe de la mine que la thermité en vrac. Ces produits procurent une flamme très linéaire qui donne des résultats plus uniformes que les produits de thermité examinés dans l'étude actuelle.

La thermité n'est pas un explosif et elle est donc plus facile et moins restrictive à transporter, stocker et manipuler pour son utilisation sur le terrain. La thermité pourrait être utile à présent durant les opérations normales de déminage humanitaire et de destruction de mines ou de mines /UXO stockées. En s'assurant que ces dernières sont désamorcées, on réduit de manière importante la probabilité de détonation.

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1. Introduction

There are several methods of mine neutralization currently employed in humanitarian and military demining operations. Depending on fuse type and sensitivity, mines are pulled from the ground using safety ropes and then destroyed by burning or using explosives. More commonly, though, destroying a mine without disturbing it (in case it is booby-trapped) is preferred, and is usually done in situ using mechanical or explosive systems. Mechanical systems tend to be too expensive to operate and maintain for many of the countries where the problem of mine clearance exists, and they cannot be relied upon to be 100% effective. Many of these countries also have a limited availability of good quality explosives and lack the safety and security to store them. In addition, reducing the mass of the explosive in the mine, as well as the mass of the neutralization charge, would minimize costs and the probability of collateral damage. Consequently, demining organizations have expressed a desire for a non-explosive method for mine destruction.

Pyrotechnic devices, which do not contain explosives, have been developed to burn, rather than detonate, the explosive within the mine. Although these pyrotechnic devices are easier to transport, their performance is uncertain and they are not as widely used as traditional mine clearance methods. The most common pyrotechnic devices used are flares such as the Thiokol *Humanitarian Demining (HD) Flare* and the DERA *FireAnt*. The Thiokol *HD Flare* contains production excess solid rocket propellant developed for the Space Shuttle. The *FireAnt* device generates a convective flow with a thermite reaction (in this case, from a mixture of aluminum and iron oxide). Both flare devices can be positioned on or near an exposed mine and ignited such that the flame is directed towards a specific location on the mine casing. Ideally, the explosive burns out without detonating.

The thermite mixture is also available in loose powder form, such as Arc Star Thermite, or pre-packaged with an igniting device, such as the *Mine Incinerator*¹. These systems rely on the melting and flow of iron due to the heat of the exothermic reaction to penetrate the mine casing and burn the explosive. They cannot be used to direct the heat towards a small area of the casing like the Thiokol *HD Flare* and the *FireAnt*.

A series of trials was performed by Defence Research and Development Canada (DRDC) Suffield from 20 May to 30 June 1998 to examine the effectiveness of thermite in neutralizing a variety of mines. In studying the effect of thermite, the following terms were used to explain how mine neutralization occurred:

Detonation: A high-speed reaction caused by a shock wave that propagates at supersonic speeds through an explosive.

¹ The *Arc Star* Thermite and *Mine Incinerator* are no longer available from their respective manufacturers. The thermite mixture could be obtained from manufacturers of supplies for Thermit® welding.

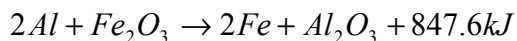
Deflagration: A slower reaction than detonation where the decomposition proceeds at a rate less than the sonic velocity of the explosive. The damage caused by deflagration is lower than that caused by detonation.

Burnout: All of the explosives in the mine combust (burn) without detonation or deflagration.

Burn-through: Process where thermite melts a local area in the casing, creating an opening that allows combustion products from the burning explosives to escape.

1.1 The Thermite Reaction

Thermite is a mixture of powdered or granular aluminum metal and powdered iron oxide. The mixture, when ignited (ignition temperature ranges from 500-800° C) is exothermic, reaching temperatures above 2500° C. At 2500°C, the iron oxide thermomelts to a water-like consistency and will free flow/fall under gravity. Thermite has traditionally been used for specialized welding operations and in incendiary munitions for military purposes. The thermitic process is only one of many self-propagating, high-temperature reactive processes currently under scientific investigation, with many metal/metal compound reactions being examined. However, this study will be restricted to the typical iron/aluminum reaction as shown below.



The amount of energy released per unit mass (reaction energy) of thermite can be calculated using the molar masses of the reactants, aluminum and iron oxide, as shown below:

$$\text{Reaction Energy} = \frac{847.6kJ}{(2mol)M_{Al} + (1mol)M_{Fe_2O_3}}$$

$$\text{Reaction Energy} = \frac{847.6kJ}{(2mol)(g/mol) + (1mol)(g/mol)} = 3.97kJ/g$$

Properties of the standard thermite composition are given in Table 1.

1.2 Thermite Use in Demining Operations

Theoretically, thermite should burn through the mine casing to cause the explosive in the mine to ignite and completely burn out without causing the fuse train to function. Should a detonation occur, sufficient explosive would have been consumed so that the explosion would be minimal.

The use of thermite on a buried mine has special problems. The soil surrounding the mine is a good thermal insulator preventing a considerable amount of the heat energy generated by the thermite reaction from reaching the mine. Heat energy is lost to the

Table 1. Properties of a Standard Thermite Mixture (Al - 23.7%, Fe₃O₄ - 76.3%) at 1 Bar Pressure

PROPERTIES	VALUES
Flame Temperature	2857° C
Gas Production	140 ml/g
Ignition Temperature	≥ 800° C
Product Heat Capacity	3.62 kJ/g
Condensed Products	Al ₂ O ₃ - 47%, melting point 2050° C Fe - 53 %, melting point 1536° C
Structure	Porous powder compact
Electrical Properties	Conductor, magnetic

atmosphere, necessitating the use of a very large amount of thermite to heat the explosive to its ignition temperature. In addition, unless the use of thermite causes the complete destruction of the mine, the mine may not be neutralized and could be left in a sensitive and unstable state. For a buried mine, there would be no visual sign to indicate that the mine is only partially destroyed. Because of these factors, thermite should be used to neutralize only exposed, flush-buried, or surface-laid mines.

In the DRDC Suffield trials, most of the mines used were exposed or flush-buried. This is consistent with standard mine clearance procedures used in humanitarian demining where mines are usually exposed in order to identify each mine. The fuse in a mine is usually located near the centre of the upper or lower surface of the mine. In order to apply the thermite as far away from the fuse as possible, different locations are chosen, depending on the type of mine encountered. For a flush-buried mine where the upper surface is exposed, thermite would most likely be applied at the edge of the mine. For a surface-laid mine where the mine is placed on the soil surface, the thermite would most likely be applied to the exposed side. Figure 1 shows the different scenarios for landmine neutralization considered in the above discussion.

Ideally, at 2500° C, the liquid iron slug from the thermite would quickly burn through a metal or plastic mine case. The explosive found in most mines is cast, non-porous TNT. The extremely high temperature of the slug would quickly cause the surface of the TNT to burn. Because of the hole in the casing, the fire is not confined, which should prevent a runaway reaction leading to deflagration or detonation. In the event that thermite has been used and a mine's explosive content has started to burn, the insulation of the surrounding soil and thermal reflection of the casing may cause the explosive to reach its critical temperature and detonate.

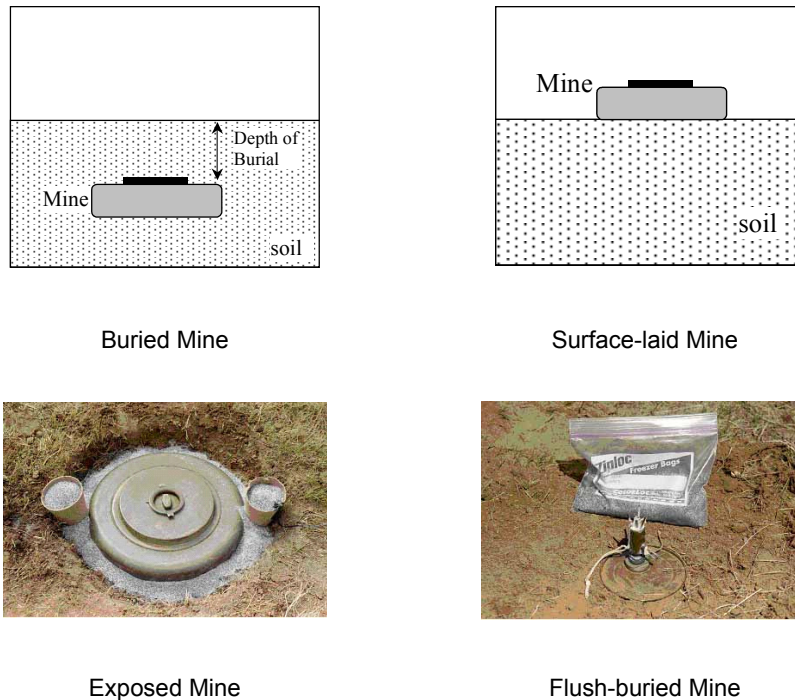


Figure 1. Different Landmine Scenarios

1.3 Problems with Thermite Mixtures

Thermite has been used for civilian and military purposes in the past but there are several problem areas that must be addressed by manufacturers before thermite products will be acceptable for humanitarian demining purposes. These problem areas are:

Metal-metal-oxide reactions are never completely gasless and produce different amounts of gases at high reaction temperatures. These gases can be toxic, similar to those produced in welding operations.

Thermite compounds are compact powder mixtures (the use of organic binders is not recommended) and therefore they are porous. The difficulty in achieving uniformity of the porous mixture could result in inconsistent effects even when the same neutralization set-up is used.

Most thermitic oxidizers, such as iron oxide, are moisture sensitive. This might change the behaviour of the thermite mixture if there is too much moisture in the environment where it is being used or stored for later use.

Should thermite cause the mine to detonate, molten iron will be thrown into the surroundings along with the metal associated with the mine itself. Pieces of the

explosive train and bulk explosive might also be spread about the immediate vicinity. This would result in potential fire hazards, explosive hazards, and metallic contamination at the site.

1.4 Thermite Advantages in Humanitarian Demining

Thermite offers several potential advantages for humanitarian demining. These include:

1. Current thermite compositions are classified as non-hazardous and non-explosive; they do not require special handling, shipment, or storage procedures.
2. Unit cost per kilogram is often much cheaper than explosives.
3. When a mine has to be destroyed in proximity to some valuable asset, thermite could minimize collateral damage provided it does not result in the detonation of the mine.

2. Heat Transfer Analysis

The heat generated by the exothermic thermite reaction can be studied by considering the heat transfer into the soil, the air, and the mine. Heat transfer analysis will determine whether or not thermite can be used as a practical neutralization method for land mines. It also makes it possible to look at how the heat generated by the reaction is partitioned in the environment so that the total amount of thermite required to neutralize a given target might be determined.

Two configurations will be considered in this analysis: neutralization of mines through a soil layer, and neutralization of mines where the thermite is in direct contact with the mine casing. In practice, flush-buried and surface-laid mines differ from exposed mines (Figure 1) in that they do not have a small excavation cavity around them into which to pour the thermite. However, the simplistic one-dimensional heat transfer model considered in this section will not differentiate between exposed and flush-buried mines. Instead, the model assumes that thermite is applied directly to the mine casing without an intermediate layer of soil between them (Figures 2 and 3). The calculations are performed for metal-cased mines, with AISI C1020 steel casings, and plastic-cased mines with rigid PVC casings. A unit area of 1cm² is considered so that the calculations may be scaled to any area, depending on the size of the mine and the layout of the thermite.

The system was modeled using transient heat transfer analysis because of the sudden rise in temperature caused by the exothermic thermite reaction. The following assumptions were made for the heat transfer calculations:

- All materials in the computation, including the mine, the soil, and the air are at the same initial temperature, i.e. 25 °C.

- The thermite maintains a constant temperature equal to the thermite flame temperature, 2857 °C, throughout the computed time.
- The heat transfer is one-dimensional.
- There is perfect contact between the thermite, soil, casing, and explosive, which implies that the temperature of any two adjacent materials will be the same at their interface.
- Once the surface of the explosive reaches its auto-ignition temperature, it starts burning. This burn is a self-propagating reaction and the explosive will burn itself out on its own.
- The calculations for the mine and the soil assume that heat is transferred through conduction only, with convection and radiation being negligible.
- Heat transfer into the air involves convection and radiation. The rates of convection and radiation are not expected to change much over the period of time considered (except at the very start of the heat transfer). So the heat transfer into air is calculated using steady-state assumptions.
- The soil is a sandy loam soil.
- The effects of confinement of the explosive by the mine casing are not investigated here.
- The calculations also do not account for the phase change associated with the thermite melting a hole through the mine casing, which will enable it to burn the explosive more effectively.

2.1 Heat Transfer into the Mine

A simple representation of a one-dimensional heat transfer from the thermite mixture to the mine is shown in Figure 2 and in Figure 3. The model considers the heat transfer from a small unit area of thermite (1 cm²) through different layers of material. Figure 2 shows the layers of soil and casing between the thermite and explosive for a buried mine. Figure 3 shows that there is only a layer of casing separating the explosive from the thermite for an exposed mine.

The usual requirement to positively identify the mine likely precludes the use of thermite to neutralize buried mines. However, it is not inconceivable that the situation could arise where the presence of a soil layer between the thermite and the mine does exist and must be investigated.

In theory, the highly exothermic thermite reaction melts the iron. The molten iron would then flow through the soil to the mine casing, melt a hole in it, and initiate the burning of the explosive.

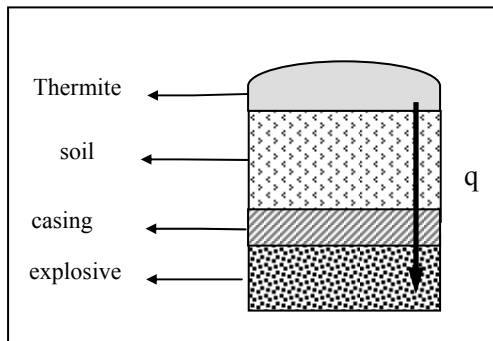


Figure 2. Heat Conduction Layers for a Buried Mine

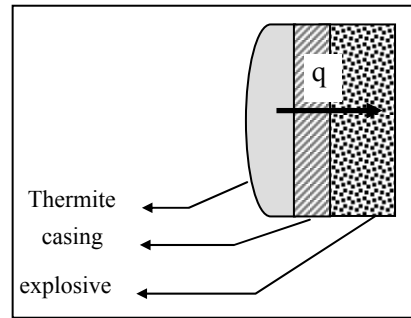


Figure 3. Heat Conduction Layers for an Exposed Mine

The transient conduction model considered in this section uses a numerical method, along with the Matlab® code (Annex A). The computations were performed separately for the buried mine case and the exposed mine case. The model assumed a sudden rise in temperature at the thermite/soil or thermite/casing interface to the flame temperature of the thermite reaction (2857 °C). It was assumed that this temperature was maintained at the interface for the time period under consideration. The initial conditions used in the computations are shown below:

Initial temperature of soil and/or casing = 25 °C

Temperature of isothermal surface near heat source = 2857 °C

For the buried mine case, it was assumed that the temperature of the casing and the soil are equal at the soil/casing interface.

The properties of the different materials used in the computation are listed in Table 2. Further details regarding the soil properties are provided in Annex B. Mine casing thickness values are approximate. The depth of burial (DOB) was selected because it is a common DOB used in field trials at DRDC Suffield.

Using the above conditions and material properties, an Euler integration of the heat equation (Annex A) was performed to obtain the temperature distribution across the soil and/or casing thickness as a function of time. The results for a few different times are shown in Figures 4 through 7. In the plots, the x direction represents the thickness of the materials under consideration, with $x = 0$ being the inner surface of the casing and the maximum x value representing the interface between the thermite and the soil or casing.

Table 2. Properties of Materials Involved in Heat Conduction into Mine

MATERIAL	PARAMETER	VALUE	
Soil	Thickness [mm]	25	
	Density [kg/m³]	1600	
	Volume [m³]	2.50E-08	
	Thermal Conductivity [W/m.K]	1.3	
	Specific Heat [J/m³/C]	2.00E+06	
Casing		Steel	PVC
		2	5
		7850	1460
		1.57E-05	7.30E-06
		51.9	0.0313
		4.18E+02	1.70E+03

Using the above conditions and material properties, an Euler integration of the heat equation (Annex A) was performed to obtain the temperature distribution across the soil and/or casing thickness as a function of time. The results for a few different times are shown in Figures 4 through 7. In the plots, the x direction represents the thickness of the materials under consideration, with $x = 0$ being the inner surface of the casing and the maximum x value representing the interface between the thermite and the soil or casing.

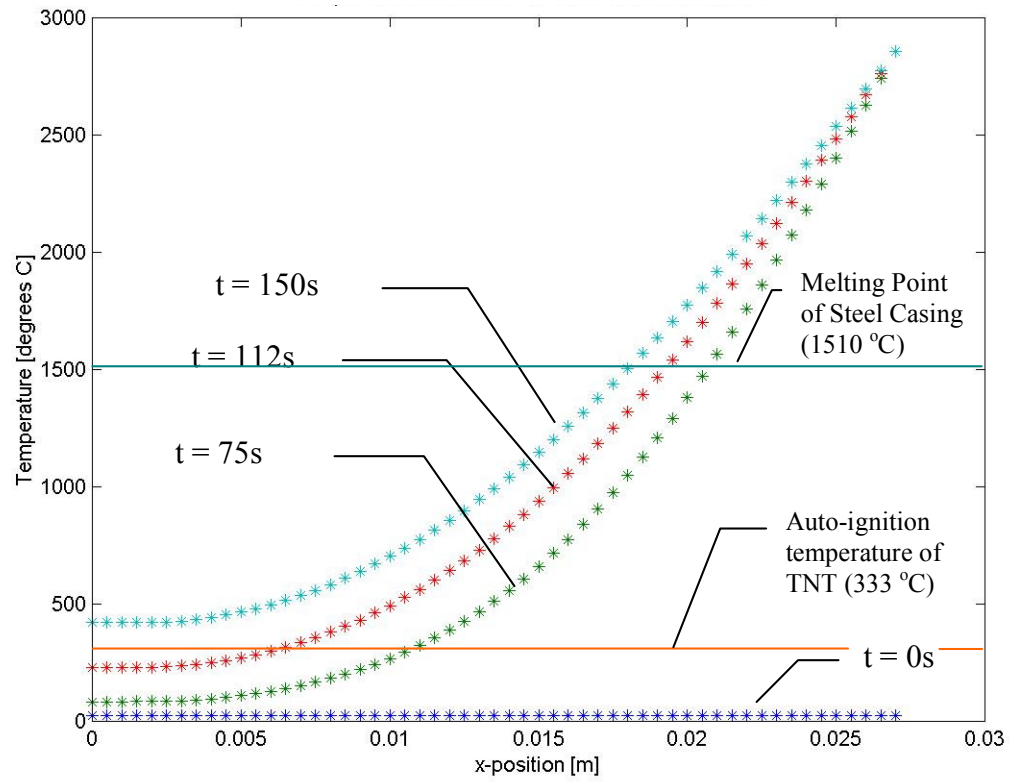


Figure 4. Temperature Distribution in the Soil and Casing for a Buried Steel Mine

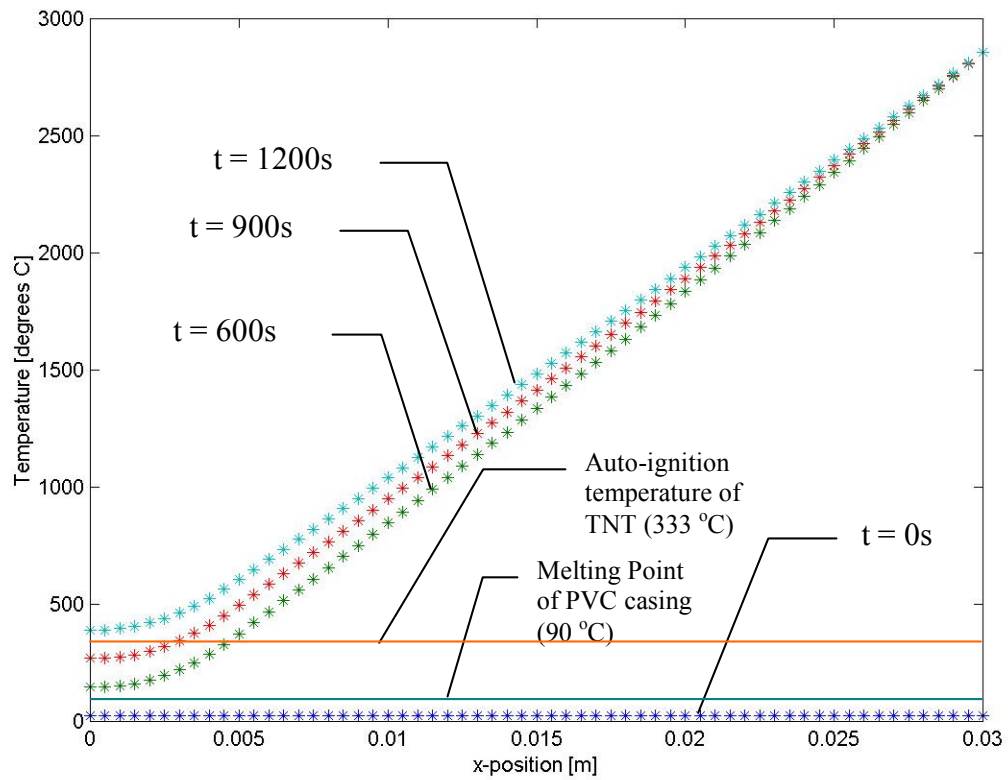


Figure 5. Temperature Distribution in the Soil and Casing for a Buried Plastic Mine

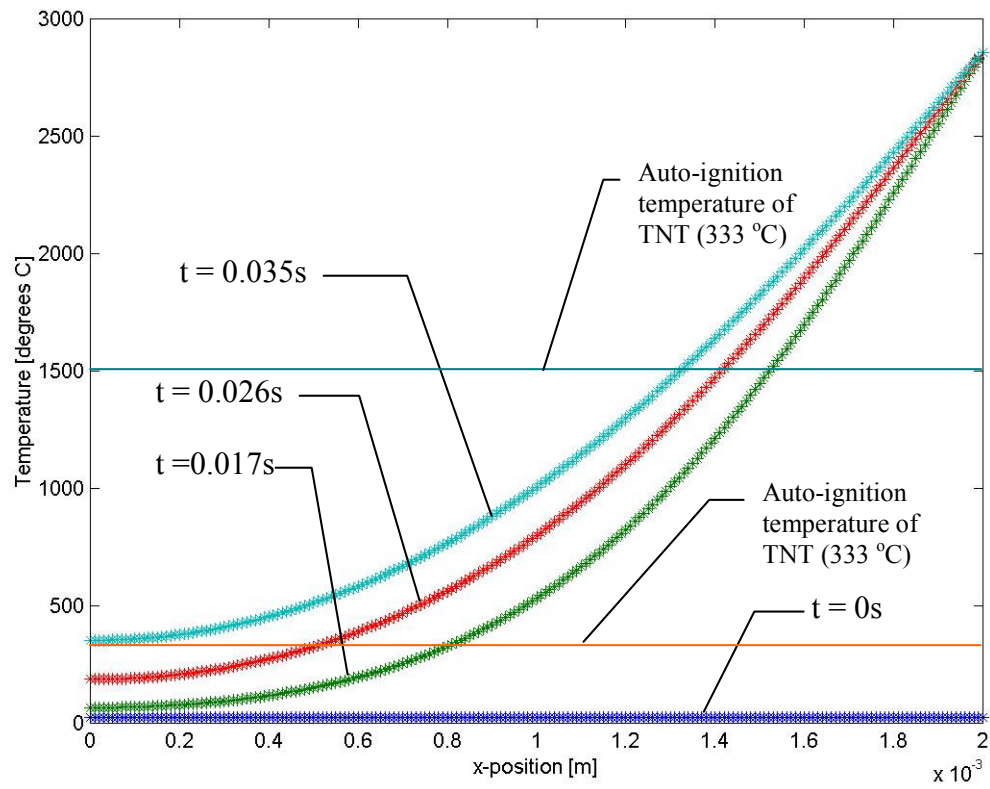


Figure 6. Temperature Distribution in the Casing for an Exposed Steel Mine

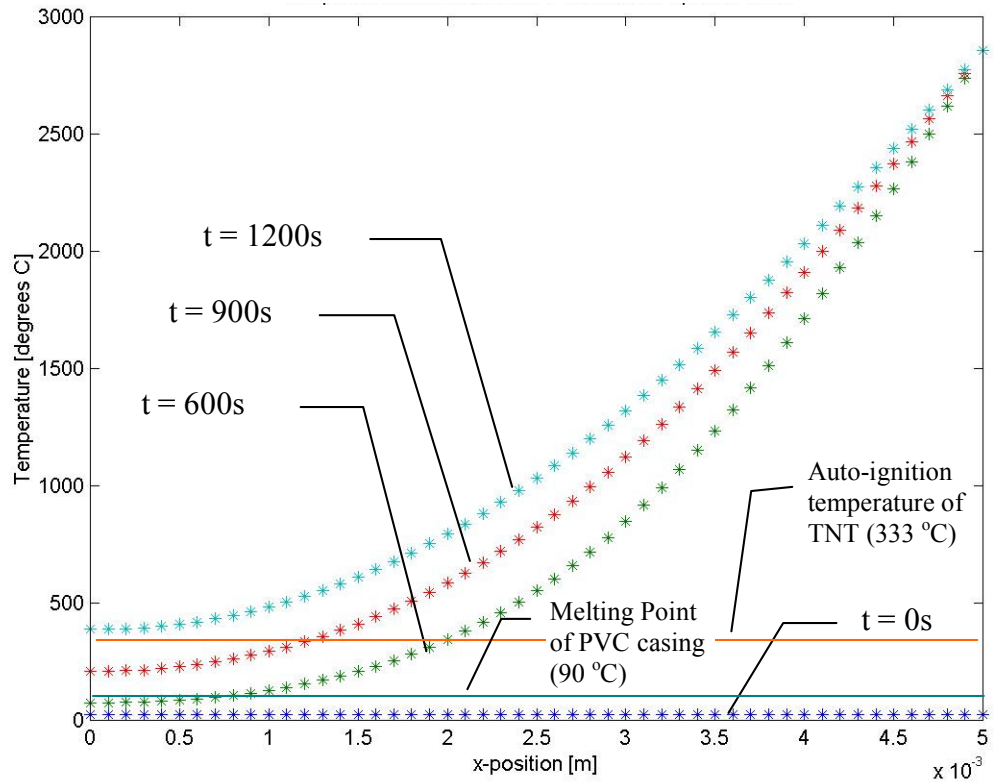


Figure 7. Temperature Distribution in the Casing for an Exposed Plastic Mine

Table 3. Heat conduction into buried and exposed mines

MINE CONFIGURATION	CASING TYPE	TIME* FOR INNER CASING SURFACE TO REACH AUTO-IGNITION TEMPERATURE OF TNT [S]	TOTAL HEAT TRANSFERRED TO MINE [J]
<i>Buried Mine</i>	Steel Casing	133	22
	Plastic Casing	1056	83
<i>Exposed Mine</i>	Steel Casing	< 1	1.1E-03
	Plastic Casing	261	2.2E-01
* The numerical approximation implies that the results are not 100% accurate and are hence rounded to the nearest second.			

Figures 4 through 7 show that the temperature gradient changes with time and material properties. It is assumed that the explosive will start burning once the inner surface of the casing is heated to the auto-ignition temperature of the explosive (333 °C for TNT). The time required for the temperature at the inner surface of the casing ($x=0$) to reach 333 °C, as indicated by the Matlab® computations, is tabulated in Table 3 for the different cases considered.

The temperature gradient at the thermite/soil or thermite/casing interface was used to determine the rate of heat transfer from the thermite towards the mine for several discrete times, as shown in Figures 8 through 11. These heat transfer rate values were then numerically integrated over the time period under consideration to compute the total heat transferred to the mine during that time period (Annex A). These values are summarized in Table 3.

The plots in Figures 8 through 11 show that the rate of heat transfer decreases in a logarithmic manner. The large drop in the rate of heat transfer at the start is attributed to the large temperature difference between the thermite (2857°C) and the casing or soil (25°C). This temperature difference decreases rapidly as the system is heated. Table 3 summarizes the heat conducted for both buried and exposed mine cases.

The values in Table 3 show that the heat transfer rate is greatest for exposed metal-cased mine, resulting in the fastest initiation of the burning of the explosive. This is due to the high thermal conductivity of metals and the absence of an intermediate insulating layer of soil. Some extra time is required to bring the critical mass of the explosive to its auto-ignition temperature in order to propagate the burn. This is particularly relevant for the exposed mine with metal casing. In this case, the temperature rise at the face of the explosive is practically instantaneous; hence the

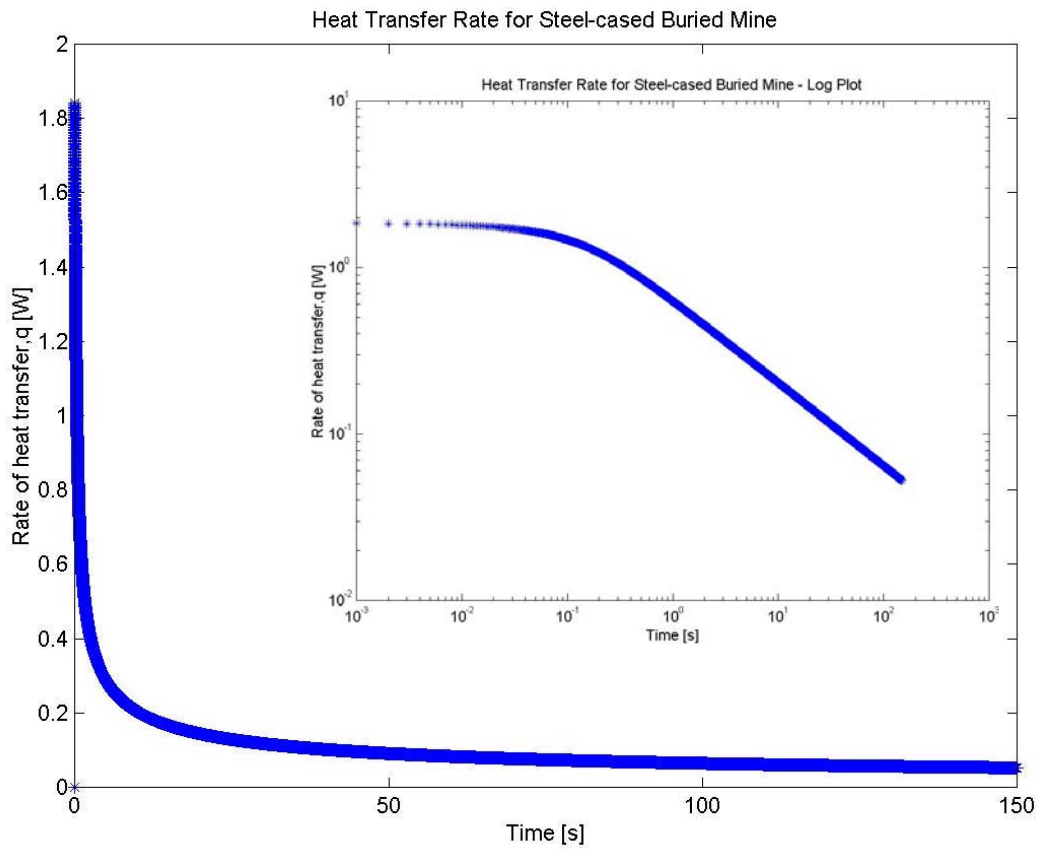


Figure 8. Heat Transfer Rates in the Soil and Casing for a Buried Steel Mine

actual ignition time is mainly driven by the time required to reach the conditions for self-sustenance. This is not as important for the other cases.

The insulating properties of soil are evident from the longer times required to start the burning of the explosive and the much larger amount of heat required when a mine is buried. This implies that so much thermite is required in this situation that the technique is impractical. Conversely, there would be a low probability of transferring heat from the intended target to a nearby mine or UXO.

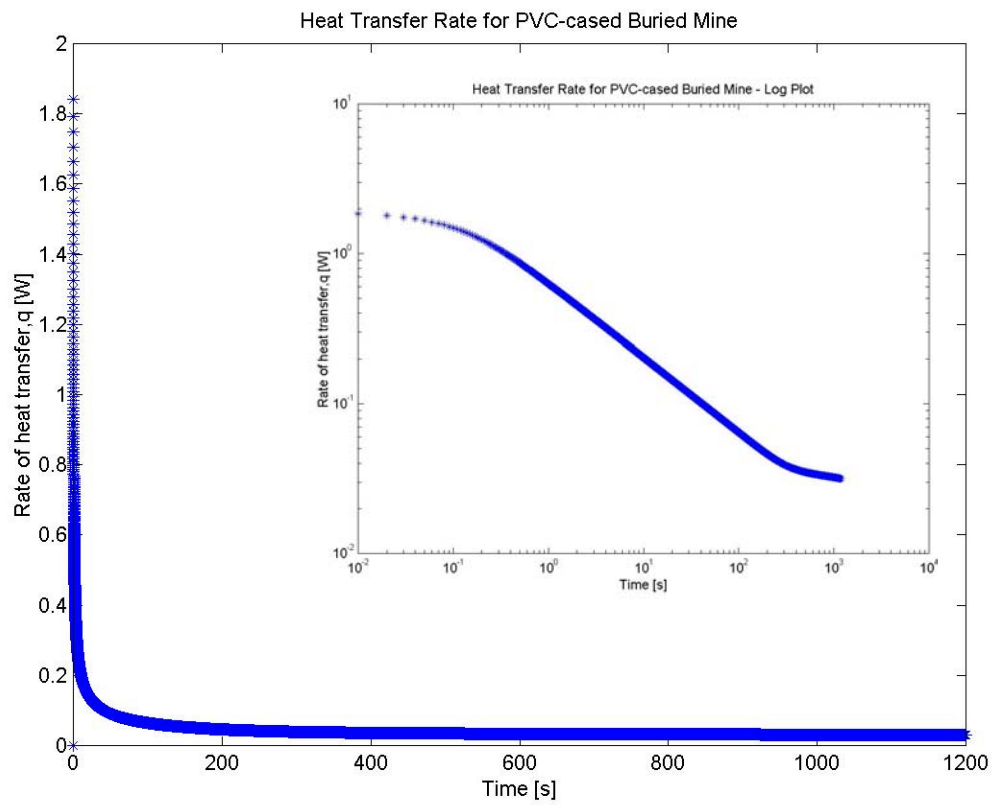


Figure 9. Heat Transfer Rates in the Soil and Casing for a Buried Plastic Mine

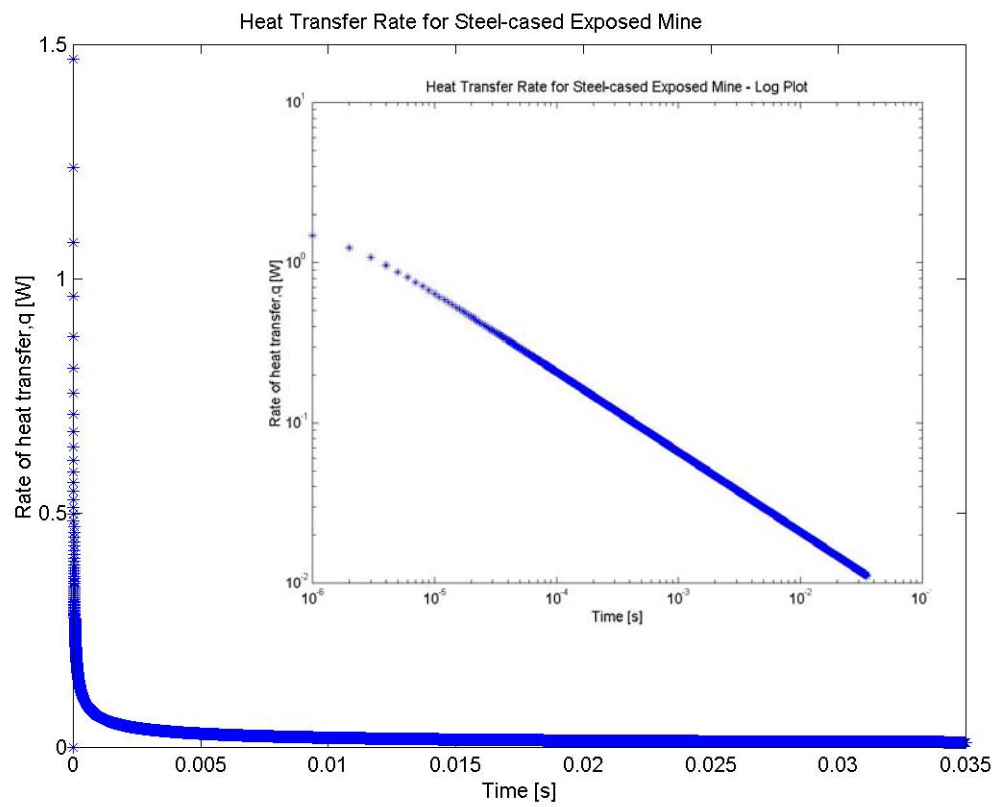


Figure 10. Heat Transfer Rates in the Casing for an Exposed Steel Mine

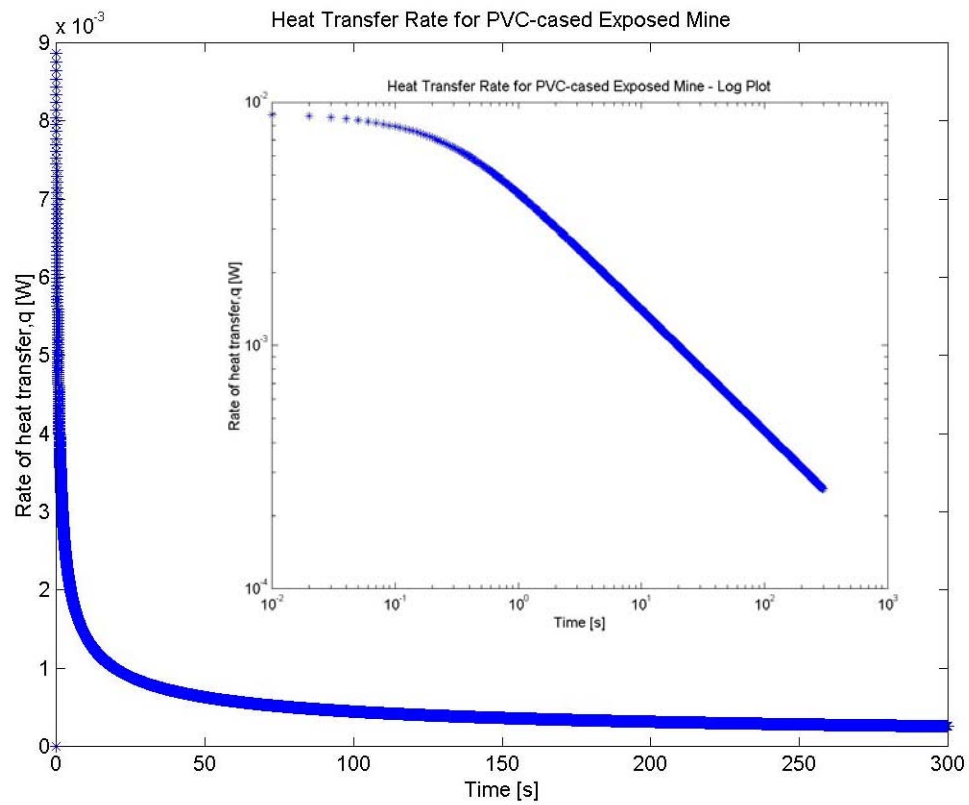


Figure 11. Heat Transfer Rates in the Casing for an Exposed Plastic Mine

2.2 Heat Loss into the Surrounding Soil

Heat lost from the thermite to the surrounding soil occurs mainly through conduction. Assuming that the thermite maintains its flame temperature of 2857 °C, transient analysis can be done by considering a semi-infinite solid (soil) with the surface temperature suddenly elevated to T_o (2857 °C). The rate of heat transfer is then given by the following equation:

$$q = \frac{dQ}{dt} = \frac{k \cdot A(T_o - T_i)}{\sqrt{\pi \cdot \alpha \cdot t}}$$

$$Q = \int \frac{k \cdot A(T_o - T_i)}{\sqrt{\pi \cdot \alpha}} t^{-1/2} dt$$

$$Q = 2 \frac{k \cdot A(T_o - T_i)}{\sqrt{\pi \cdot \alpha}} t^{1/2}$$

where

q = rate of heat transfer [W]

Q = heat energy transferred [J]

t = time [s]

k = thermal conductivity [W/m.K]

A = area [m²]

T_o = temperature of surface [K]

T_i = initial temperature of solid [K]

$$\alpha = \text{thermal diffusivity [m}^2/\text{s}] = \frac{k}{\rho \cdot c_p}$$

ρ = density [kg/m³]

c_p = specific heat at constant pressure [J/kg °C]

Using the properties for soil from Table 2, the heat lost into the soil over a time interval can be evaluated as shown below.

$$\alpha = \frac{k}{\rho \cdot c_p}$$

$$\alpha = \frac{(1.3 \text{ W} / \text{m} \cdot \text{K})}{(1600 \text{ kg} / \text{m}^3)(1250 \text{ J} / \text{kg} \cdot \text{K})} = 6.5 \times 10^{-7} \text{ m}^2 / \text{s}$$

$$Q = 2 \frac{k \cdot A(T_o - T_i)}{\sqrt{\pi \cdot \alpha}} t^{1/2}$$

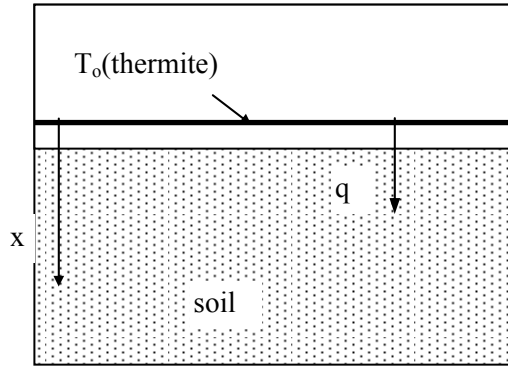


Figure 12. Heat Loss into a Semi-infinite Solid from an Isothermal Surface

Sample Calculation:

For the steel-cased buried mine, the time interval under consideration is 133s. Therefore the heat lost to the soil during this time period is:

$$Q = 2 \frac{(1.3W / m.K)(1 \times 10^{-4} m^2)(2857 - 25)K}{\sqrt{\pi(6.5 \times 10^{-7} m^2 / s)}} \sqrt{133s}$$

$$Q = 5953J$$

Similarly, the total heat loss to the soil was calculated for the other scenarios as summarized in Table 5, Section 3.4.

2.3 Heat Loss into the Atmosphere

The heat transfer from the surface of the thermite into the atmosphere can be modelled by a horizontal plate exposed to free convection. The relevant equations are shown below:

Rate of Heat Transfer :

$$q = \bar{h}A(T_{thermite} - T_{ambient})$$

Heat Transfer Coefficient :

$$h = Nu_f \left(\frac{k}{L} \right)$$

The calculation of the heat transfer rate then requires several factors that have been tabulated in Table 4 below.

The thermal properties were obtained from J.P. Holman, 1997 [5].

Using these values, and considering a unit area of $1cm^2$, the heat loss into the atmosphere by free convection can be calculated as shown below:

$$h = Nu \left(\frac{k}{L} \right) = (9.83637) \left(\frac{0.0766W / m^{\circ}C}{0.01m} \right)$$

$$h = 75.35W / m^2 \text{ } ^{\circ}C$$

$$q_{conv} = hA(T_{thermite} - T_{ambient}) = (75.35W / m^2 \text{ } ^{\circ}C)(1 \times 10^{-6} m^2)(2857^{\circ}C - 25^{\circ}C)$$

$$q_{conv} = 0.2134W$$

Table 4. Convection Heat Transfer Parameters

PARAMETER	VALUE	DESCRIPTION
Film Temperature T_f [K]	1168	$\frac{T_{thermite} + T_{ambient}}{2}$, the temperature at which the other factors are calculated
Characteristic length L [m]	0.01	length of side for a square
Prandtl Number Pr_f	0.706	
Thermal Conductivity of air k_f [W/m °C]	0.0766	
Volume Coefficient of Expansion: β [K ⁻¹]	0.000856	$\beta = 1/T_f$
Kinematic Viscosity of Air ν_f [m ² /s]	1.5254×10^{-4}	
Grashof Number Gr_f	155932	$Gr_f = \frac{g\beta(T_{thermite} - T_{ambient})L^3}{\nu^2}$
C, m	0.54, 0.25	Constants determined from the product $Gr_f Pr_f$
Nusselt Number Nu_f	9.836	$Nu_f = C(Gr_f Pr_f)^m$

The heat loss by radiation can be calculated using the following equation:

$$h = Nu \left(\frac{k}{L} \right) = (9.83637) \left(\frac{0.0766 W / m^{\circ} C}{0.01 m} \right)$$

$$h = 75.35 W / m^2 \cdot ^{\circ} C$$

$$q_{conv} = hA(T_{thermite} - T_{ambient}) = (75.35 W / m^2 \cdot ^{\circ} C)(1 \times 10^{-6} m^2)(2857^{\circ} C - 25^{\circ} C)$$

$$q_{conv} = 0.2134 W$$

The heat loss by radiation can be calculated using the following equation:

$$q_{rad} = \varepsilon \cdot A \cdot \sigma(T^4 - T_{\infty}^4)$$

where

$$q_{rad} = \text{rate of heat transfer by radiation [W]}$$

ϵ = emissivity

σ = Stefan-Boltzmann constant = $5.6697 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$

T = temperature of the radiating surface [K]

T_{∞} = temperature of a large surrounding surface (approximating the atmosphere) = 25 °C

The emissivity of the thermite will be approximated by considering a mixture of 75% oxidized iron ($\epsilon = 0.31$) and 25% aluminum ($\epsilon = 0.05$). Using a weighted average, the emissivity of thermite is approximated to be 0.245. The rate of heat loss into the atmosphere by radiation can then be calculated as follows:

$$\begin{aligned}q_{rad} &= \epsilon \cdot A \cdot \sigma (T^4 - T_{\infty}^4) \\q_{rad} &= (0.245)(1 \times 10^{-4} \text{ m}^2)(5.6697 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)((3130 \text{ K})^4 - (298 \text{ K})^4) \\q_{rad} &= 133.3 \text{ W}\end{aligned}$$

The above calculations show that the loss of heat to air is far greater by radiation than by convection.

The total heat loss to the atmosphere over a period of 133 seconds (t_{total}) can be approximated by adding the heat transfer by convection and by radiation and multiplying the sum by the total time. This computation assumes that the rates of heat transfer remain almost the same during the time period considered. However, it is apparent that the rates actually decrease in time (although not as fast as the conduction heat transfer rate in the soil and casing). Therefore, this result overestimates the heat loss to the atmosphere.

$$Q_{air} = (q_{conv} + q_{rad})t_{total}$$

Sample Calculation:

For a buried steel-cased mine, it takes 133s for the inner casing surface to reach the auto-ignition temperature of TNT. Therefore the total heat lost to air during this time period is:

$$\begin{aligned}Q_{air} &= (0.2134 \text{ W} + 133.3 \text{ W})(133 \text{ s}) \\Q_{air} &= 17824 \text{ J}\end{aligned}$$

2.4 Total Heat Transfer

The total heat (Q_{sum}) is calculated by summing the heat transferred from the thermite into the mine (Q_{mine}), soil (Q_{soil}), and air (Q_{air}). Total heat is then used to find an approximate amount of thermite required to burn the explosive in a 1 cm^2 area. The exothermic thermite reaction generates 3.97 kJ/g of heat energy as shown in Section 1.1. Using the heat energy of the reaction, the corresponding amount of thermite can be determined from the following equation:

$$\text{Mass of Thermite} = \frac{Q_{\text{sum}} [\text{J}]}{\text{Reaction Energy} [\text{J/kg}]} = \frac{Q_{\text{sum}} [\text{J}]}{3.97 \text{ J/kg}}$$

Table 5 summarizes the heat transfer and amounts of thermite required for the buried and exposed mine cases.

Table 5. Summary of Total Heat Transfer from Thermite

MODE OF HEAT TRANSFER	AMOUNT OF HEAT TRANSFER [J]			
	<i>Buried Mine</i>		<i>Exposed Mine</i>	
	<i>Steel Casing</i>	<i>Plastic Casing</i>	<i>Steel Casing</i>	<i>Plastic Casing</i>
Conduction into MINE	2.2E+01	8.3E+01	1.1E-03	2.2E-01
Conduction into surrounding SOIL	6.0E+03	1.7E+04	9.5E+01	6.6E+03
Convection and Radiation into AIR	1.8E+04	1.4E+05	4.5E+00	2.2E+04
TOTAL	2.4E+04	1.6E+05	9.9E+01	2.8E+04
Time	133	1056	< 1	163
Amount of thermite required [g]	6	40	2.5E-02	7

Table 5 indicates that a plastic mine would require more thermite per square centimetre than a metal mine. This is because it takes longer to ignite the explosive in a plastic casing, which implies that there is more time for heat loss into the atmosphere and soil. These theoretical results suggest that thermite is most effective against an exposed steel mine. However, these simple calculations do not take into account the time required to ignite the critical mass of thermite needed for propagation of the burn and the two-dimensional heat effects in the mine casing. For a metal casing, in particular, the heat would be quickly conducted from the area in contact with the thermite to other areas of the casing, including the area near the fuse well, which might set off the fuse.

Many plastics melt at lower temperatures than metals. Thermite would easily penetrate a plastic casing by melting through it. The holes created in the plastic casing would also negate containment issues that favour detonation. Metal casings have higher melting temperatures and thermite would likely take more time to penetrate, contact the explosive, and initiate burning. These considerations were not represented in this

heat transfer model. The analysis also did not consider the two-dimensional heat effects in the mine casing. When heated, a small area of a metal mine casing would conduct the heat to the surrounding casing faster than a plastic mine. This has implications for the initiation of the fuse and for the dissipation of heat in the casing of a metal-cased mine.

3. Materials and Methods

The trials reported in this Technical Report were conducted at DRDC Suffield between February and June, 1998. Two thermite products were evaluated for their effectiveness against a variety of anti-tank (AT) and anti-personnel (AP) mines. The trials were conducted to examine the effects of thermite when used against exposed and partially exposed, fused land mines; and to attempt to optimize thermite quantities and attack patterns to achieve complete burning and destruction.

3.1 Thermite Products

The two thermite products used in these trials were the CIL/Evan Incorporated *Arc Star*, and the DEW Engineering *Mine Incinerator*.

Arc Star is a thermite product (a loose powder consisting of iron oxide 60.8 %, aluminum 19.5 %, steel 14.6 %, iron 5.1 %, and manganese 0.8 %; all percentages are by weight). It ignites at approximately 1080 °C, and burns at approximately 2500°C. The material was delivered in 0.45 kg (1 lb) plastic bags. The material is not classified as an explosive, and is safe to store and transport.

Mine Incinerator is a self-contained unit that consists of a metal or plastic container filled with a thermite mixture and its igniter. Two variants of the *Mine Incinerator* were tested. The heavier Type 3a is encased in metal and comes with an adjustable tripod standoff device. The smaller Type 4 charge has no metal case or tripod; it must be placed directly in contact with the target. The ignition temperature for these charges is given as 350°C, with a burning temperature of 2500 °C. It has a DOT (Department of Transportation) classification 4.1 (flammable solid), which is non-explosive.

Thermite causes electromagnetic interference with instrumentation while it is reacting. During the current research, the signals from thermocouples buried close to the reaction were adversely affected by that noise and the data received was unusable.

The thermite products were applied to a variety of fully exposed and partially buried AT and AP mines. Trials with fully buried mines were later deemed unnecessary due to the inconsistencies in the results of the trials. The mines used in the trials were selected to represent a wide range of mine types and casing materials. The characteristics of the mines employed in these trials are listed in Table 6. Further details about each mine can be found in Annex C.

Table 6. Mine Characteristics

NAME	MINE TYPE	CASING MATERIAL	MINE WEIGHT [KG]	EXPLOSIVE
M15	AT blast	Steel	14.27	10.33kg Composition B plus an 11g RDX booster
M16A2	AP bounding fragmentation	Steel	2.83	590 g of TNT plus an 11 g booster of Comp A5
PT Mi-Ba-III	AT blast	Bakelite	9.9	7.2 kg of Cast TNT, 116 g booster pressed TNT
M21	AT penetrator	Steel	7.9	5 kg of H6
PP-Mi-Na-1	AP blast	Plastic	0.175	93 g of TNT

Information in this table is drawn from the Canadian Forces landmine database [6]

3.2 Soil

Prairie soil was used for all trials. The general properties of a sample of the soil obtained from the test site [7] are listed in Table 7.

Table 7. Soil Properties of Soil from Test Site

PROPERTY	VALUE
Moisture content	14.6 %
Bulk density	1841 kg/m ³
Void ratio	0.67
Soil description	Clay, silty, sandy, brown, low plastic

3.3 Trial Set-up

The thermite charge was placed in contact with the mine casing and was remotely ignited with electrical initiation. In some cases, several charges were placed around the mine and ignited simultaneously. Data acquisition for these trials consisted of video and time records of the burning, and visual inspection after each test. Specific details about each trial are given in Annex D (*Arc Star*) and Annex E (*Mine Incinerator*).

3.3.1 Arc Star Thermite

Thermite was generally applied around each mine in a manner that was intended to maximise burn-through and auto-ignition of the explosive content while avoiding the fuse area. Various configurations tested included pouring loose thermite around different mine features, placing thermite in bags and putting them on or near the mine, and using cardboard containers or cups to focus the thermite heat on certain areas of the mine. Heat barriers and moisture sources were also used in some trials. The thermite burning process was started using electric igniters supplied with the *Arc Star* product. All variables considered during the execution of trials have been summarized in Table 8.

Table 8. Trial Variations Investigated for ArcStar Thermite Trials (page 1 of 2)

VARIABLES		ILLUSTRATION	DESCRIPTION	PURPOSES
VARIATION 1				
Loosely poured thermite in trench	Trench width and depth	 Loosely poured thermite.	The thermite trenches are ring shaped around the partially exposed mine. During the trials, they have been filled to the upper perimeter of the mine, or up to half of the mine height. The width of the trench also varies. There are both wide and narrow trenches. A wide trench is considered to have the width of half of the mine or greater while a narrow trench has less than half of the mine width.	To burn the explosive out of the mine.
	Quantity of loosely poured thermite around the mine		0.5kg (1 lb), 0.7 kg (1.5 lb), 1 kg (3 lb), 1 kg (4 lb), or 2 kg (5 lb)	
VARIATION 2				
Focusing containers	Number of focusing containers	 One of three focusing containers	1, 2, 3, or 4 ceramic flower pots	To allow a more concentrated amount of thermite to penetrate the mine.
	Quantity of thermite in each focusing container		0.5 kg (1 lb) or 0.9 kg (2 lb)	
	Location of focusing container		The location of the focusing container is either directly beside the mine or beside the mine with a few centimetres of loosely poured thermite in between the mine and container.	The directional container ensures that the molten mass streams towards the mine.
	Focusing container directional		Some containers have a tape-covered hole as a means of directing the molten thermite.	

Table 8. Trial Variations Investigated for ArcStar Thermite Trials (page 2 of 2)

VARIABLES		ILLUSTRATION	DESCRIPTION	PURPOSES
VARIATION 3				
Thermite bag	Quantity in a bag of thermite	 Thermite bag on a fuse well	Thermite bags are plastic Ziploc bags. Each bag contains one pound of thermite.	To allow a more concentrated amount of thermite, but less concentrated than the focusing containers, penetrate the mine.
	Location of thermite bag		Beside the fuse, on the fuse well, or in a crater on the side of the buried mine	
VARIATION 4				
Heat barriers			The heat barriers are paper dams that retain heat.	To prevent as much heat loss as possible.
VARIATION 5				
Moisture Sources			Wet paper towels were placed either over the thermite focusing containers or over a paper heat barrier.	To slow down the heat transfer rate to the mine.

3.3.2 Mine Incinerator Thermite

Each *Mine Incinerator* was placed at the top outer edge of an exposed test mine. The thermite charge was placed so that there would be optimal contact with the target mine, but it was offset from the fuse train to avoid premature detonation (Figure 13). The thermite was ignited remotely, and the burning process was allowed to proceed to completion.

All trials were recorded on three standard Sony Hi 8 video sets, and by a 1000 frame per second high-speed video camera. After the burn was complete, or detonation had occurred, the site was visually inspected, and the crater size and any resultant debris were recorded.



Figure 13. DEW Thermite Charge Placement

4. Results

4.1 CIL/Evan *Arc Star* Thermite

4.1.1 General Observations

CIL/Evan *Arc Star* was easy to handle and could be used in several different configurations. However, it was time-consuming to pour the material around the mines, and to place it in cups with cloth coverings (30 seconds – 2 minutes). After the thermite was ignited, the burn front appeared to spread through the material in less than one second, with the molten iron usually burning through the mine casing quickly (less than 10 seconds for a metal-cased mine). The mine's explosive content would then commence burning, with an extremely hot plume of flame erupting from the burn-through holes. Burn fronts from the points of initiation appeared to burn inwards towards the fuse wells. The burning inside the mine would continue until the mine fuse activated and detonated the remaining explosive, or until the explosive contents were completely burned out.

4.1.2 Trial Data

Table 9 summarizes the data recorded from the various trials. Details regarding the set-up and results for each trial are given in Annex D. Examination of the physical remains of the mines, of any resultant craters, and of the video footage was used to estimate how much explosive material remained at the time of fuse activation, when the mines detonated.

The dimensions of the craters are written as diameter x depth. Where detonation took place without the mention of residual explosive, it is implied that the entire mass of explosive in the mine detonated.

Table 9. CIL/Evan ArcStar Results (page 1 of 6)

MINE	EXPLOSIVE [KG TNT]	THERMITE USED	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
Anti-Tank							
M15 AT/steel	10.3	0.9 kg (2 lb)		15"	3' 34"		Detonation of residual explosive, crater 1.3 m x 0.5 m. 3-5kg TNT at time of detonation
M15 AT/steel	10.3	0.9 kg (2 lb)		9"	6' 01"		Detonation, crater 0.7 m x 0.2 m
M15 AT/steel	10.3	3 kg (6 lb)		1'6"	30'		Complete burnout

Table 9. CIL/Evan ArcStar Results (page 2 of 6)

MINE	EXPLOSIVE [KG TNT]	THERMITE USED	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
M15 AT/steel	10.3	3 kg (6 lb)		28"	3' 17"		Detonation of residual explosive, crater 1.3 m x 0.5 m 3-5 kg TNT at time of detonation
M21 AT/steel	4.9	2 kg (5 lb)		6"	2' 30"		Complete Burn Out
M21 AT/steel	4.9	2 kg (5 lb)		5"	1' 33"		Complete Burn Out

Table 9. CIL/Evan ArcStar Results (page 3 of 6)

MINE	EXPLOSIVE [KG TNT]	THERMITE USED	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
M21 AT/steel	4.9	2 kg (5 lb)		6"	1' 05"		Detonation of residual explosive, crater 1.0m x 0.7m 2-3 kg explosive at time of detonation
PT-Mi-Ba III AT/bakelite	7.2	0.5 kg (1 lb)		unknown	N/A	Unavailable	Demolition required
PT-Mi-Ba III AT/bakelite	7.2	3 kg (6 lb)		1'6"	26' 05"		Complete burn out

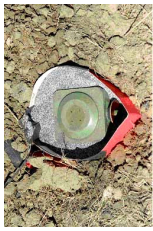
Table 9. CIL/Evan ArcStar Results (page 4 of 6)

MINE	EXPLOSIVE [KG TNT]	THERMITE USED	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
PT-Mi-Ba III AT/bakelite	7.2	5.0 kg (11 lb)		40"	14' 28"		Small Detonation of residual explosive. Small crater
PT-Mi-Ba III AT/bakelite	7.2	4 kg (8 lb)		23"	19' 04"		Small Detonation of residual explosive
Anti- Personnel							
M16A2 AP/steel	0.601	0.5 kg (1 lb)		24"	2' 31"	unavailable	Normal mine function and detonation

Table 9. CIL/Evan ArcStar Results (page 5 of 6)

MINE	EXPLOSIVE [KG TNT]	THERMITE USED	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
M16A2 AP/steel	0.601	0.9 kg (2 lb)		9"	Unknown		Complete Burn Out
M16A2 AP/steel	0.601	0.9 kg (2 lb)		1' 26"	2' 56"		Complete Burn Out
M16A2 AP/steel	0.601	1.1 kg (2.5 lb)		32"	3' 33"		Normal Mine Detonation
PPM1Na1 AP/plastic	0.093	0.5 kg (1 lb)		Almost immediately	2' 16"		Detonation of residual explosive. Very little un-burnt explosive

Table 9. CIL/Evan ArcStar Results (page 6 of 6)

MINE	EXPLOSIVE [KG TNT]	THERMITE USED	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
PPMNa1 AP/plastic	0.093	0.5 kg (1 lb)		11"	9' 11"		Complete Burn Out
PPMNa1 AP/plastic	0.093	0.5 kg (1 lb)		53"	1' 59"		Small Detonation of residual explosive
NOTE: The dimensions of the craters are written as diameter x depth							

4.2 DEW Mine Incinerator

4.2.1 General Observations

The DEW *Mine Incinerator* was simple and quick to install against the exposed mine, provided the mine was level and had a large flat upper surface. The Type 3a charges could be adjusted for height and standoff, but the individual legs were not adjustable to adapt to the contour of the mine. The Type 4 charge had no standoff mechanism, and ensuring a good contact to the mine's surface could pose problems if the system were employed under circumstances that are less than ideal. This technique might not be widely accepted in the demining community because contact with the mine, particularly the upper surface, is generally avoided.

The *Mine Incinerator* was observed to burn through the casing and explosive in the same manner as the *Arc Star* thermite.

4.2.2 Trial Data

Thermite quantity, burn-through times, and detonation times can be found in Table 10. Crater sizes can also be found in Table 10 with the exception of the M16A2 bounding AP mines, which underwent a normal bounce/detonation sequence.

Further details for the *Mine Incinerator* trials can be found in Annex E.

Table 10. DEW Trial Data Summary (page 1 of 2)

MINE	EXPLOSIVE [KG TNT]	THERMIT E USED [KG]	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
Anti-Tank							
M15	10.3	0.5 (1 lb)		58"	13' 08"		Detonation of residual explosive, crater 1.5m x 0.5m ≈4kg un-burnt explosive
M15	10.3	0.5 (1 lb)	Same as above	46"	14' 14"	unavailable	Detonation of residual explosive, crater 1.8m x 0.75m ≈5kg un-burnt explosive
M15	10.3	0.5 (1 lb)	Same as above	32"	11' 34"	unavailable	Detonation of residual explosive, crater 2.0m x 0.5m ≈4kg un-burnt explosive
PT-Mi-Ba III	7.2	0.5 (1 lb)		5"	31' 03"		Detonation of residual explosive <100g un-burnt explosive

Table 10. DEW Trial Data Summary (page 2 of 2)

MINE	EXPLOSIVE [KG TNT]	THERMIT E USED [KG]	SETUP	TIMINGS [MIN. SEC.]		OUTCOME	RESULTS
				BURN THROUGH	FINISH		
PT-Mi-Ba III	7.2	2 x 0.2 (1/2lb)		6"	29' 35"		Detonation of residual explosive <100g un- burnt explosive
Anti- Personnel							
M16A2	0.602	0.5 (1 lb)		28"	5'29"	unavailable	Normal mine detonation
M16A2	0.602	0.5 (1 lb)		07"	7"	unavailable	Normal mine detonation

5. Discussion

5.1 CIL/Evan *Arc Star* Thermite

In all cases, the thermite was able to quickly breach the mine case and initiate burning of the explosive content. Burn-through was normally achieved in metal-cased mines in less than 10 seconds and in bakelite-cased mines in approximately 60 seconds. The metal shell provided a path for faster heat conduction than the plastic and Bakelite cases, averaging roughly 4.5 minutes to detonation.

In most cases, the mine fuse appeared to activate when the flame front breached the fuse well, detonating the remainder (about 20–30 %) of the explosive. This normally resulted in a 1 m by 0.5 m crater for the AT mines. There were no craters for most AP mines because burn out or an insignificant detonation resulted. The exception was for the M16A2 bounding AP mines. When the core of these mines activated, the main charge was still mostly intact. Due to the geometry of this mine, the thermite had to be placed near the fuse. The metal casing of the M16A2 would have immediately conducted the heat to the fuse, thus setting it off.

In roughly 25% to 33% of the trials, there was no explosion, and the mine simply burned itself out. The time to completely burn the explosive was short for the AP mines (less than 2 minutes), moderate for the metal-cased AT mines (average time of 4.5 minutes), and long for the Bakelite mines (average of 20 minutes).

The following is a list of factors affecting the performance of the thermite:

Amount of Explosive in the Mine: Theoretically, the smaller the amount of explosive in the mine, the faster it will burn out and the smaller the amount left un-burnt in the event that the fuse is ignited, resulting in a detonation. Of the seven trials done with mines containing less than one kg of explosive, only two trials resulted in an explosion, both with the bounding mine, M16A2. Of the eleven trials done with mines containing more than one kg of explosive, four trials resulted in a high order detonation. This indicates that the use of thermite is more successful against mines with a smaller amount of explosive. The exception of the bounding mine implies that the geometry of the mine may also be a factor in the successful neutralization of the mine.

Amount of Thermite: The amount of thermite should be sufficient to initiate burning of the explosive, since the burning process is thereafter self-sustaining. When the amount of thermite was varied, definite trends were difficult to isolate. Burning seemed to depend more on the manner in which the thermite was placed on or around the mine

Casing Material: Thermite appears to be more effective against plastic-cased mines than against metal-cased mines. The thermite neutralized 86% of the plastic-cased

mines, but only 45% of the steel-cased mines, without a high order detonation. One possible reason for this observation is that the metal casing conducts the heat from the thermite to the fuse faster and has a better chance of initiating the fuse before the entire explosive content has burned. The metal casing might also provide more confinement than the plastic casing, resulting in higher temperatures and pressures and therefore increasing the likelihood of a detonation.

Placement of a Concentrated Source of Thermite: If a single source (such as one bag or one pot) of thermite was used, then it was placed as far from the fuse as possible while still maintaining contact with the mine. There was only one exception: when a one-pound bag of thermite was placed in the fuse well for the PT-Mi-Ba III mine, the thermite reaction could not ignite the explosive or the fuse. Instead, it created a mass of molten metal that did not penetrate the Bakelite and eventually cooled off, leaving the mine in a possibly unstable condition (this mine was later destroyed in situ). If two or more pots were used, they were placed symmetrically around the mine, where the fuse was in the center of the mine. This enabled multiple entry-points for the thermite and helped to burn more explosive in a shorter time.

Thermal Barrier: The purpose of using a paper or cardboard dam around the thermite was to minimize heat loss into the environment. The concept worked in the two trials in which the technique was used. However, these tests do not conclusively support the use of a thermal barrier because their success could also have been due to other factors such as the use of a moisture source and the choice of target mine.

Moisture Source: Wet paper towels were used in several trials to trap some of the heat that would otherwise be lost through radiation. This tended to improve the effectiveness of the heat transfer through the mine case and allow more explosive to burn before the fuse was ignited. Only two of the eight trials that used wet paper towels resulted in a high order detonation.

Type of Mine: The M15 anti-tank mine detonated in three out of the four trials where it was used. It burned completely only once. Thermite was also found to be ineffective against the bounding mine, M16A2, for which the bounce mechanism was set off in two of the four trials. Even when the successful trial against the M16A2 (with a cup of thermite and a wet paper towel on top) was repeated, it resulted in a detonation the second time.

These observations show a great deal of variability. The degree of uncertainty associated with the use of thermite is compounded by the fact that there is also variability in the exact manner that an initiator ignites the product. Based on these trials, there does not seem to be a good likelihood that a consistent, effective neutralization technique could be developed for AT mines using these thermite products.

5.2 DEW Mine Incinerator

The DEW *Mine Incinerator* detonated all target AT and AP mines in this trial series. The metal M15 mines detonated with an estimated 50-60% (4-5 kg) of the explosive remaining. Both M16A2 mines were activated by the burning process, causing the mines to function normally. Detonations in the bakelite PT-Mi-Ba III mines occurred after the majority of the explosive was burned off—it is estimated that only 100 g of explosive remained at the time of detonation.

As in the CIL/Evan *Arc Star* trials, the metal-cased mines conducted heat to the fuse well faster than the plastic and Bakelite mines, averaging 13 minutes to detonation in comparison to the 30.5 minutes average time for the Bakelite PT-Mi-Ba III mines. The AP M16A2 mine burn-through time was relatively short at an average of 3.6 minutes.

The *Mine Incinerator* product is comparable to the bag and focusing container used in the CIL/Evan trials because it is a concentrated heat source that will penetrate the mine at its point of application. The AP M16A2 mine detonated whether a single bag of *Arc Star* or a single *Mine Incinerator* was used. For the PT-Mi-Ba III, thermite (both in the DEW as well as the CIL/Evan products) is generally a fairly successful deflagration method. This could be due to the insulating property of Bakelite, which prevents rapid heat transfer to the fuse.

The DEW trial results differ from the CIL/Evan trial results in two ways. For the anti-tank M15 mine, the crater size from the detonation was observed to be bigger in the DEW trials. Also the DEW trials appeared to yield more consistent results for similar set-ups than the CIL/Evan trials. This could be attributed to the different techniques and geometries used in laying out the CIL/Evan *Arc Star* powder, which was not a factor for the pre-packaged DEW *Mine Incinerator*.

Placement difficulties could arise with the DEW charges if the target mine is not level. Adjustable standoff legs would be useful.

5.3 Exothermic Processes to Neutralize Mines

The mix of results obtained during these tests forces a re-examination of how exothermic processes should be used to neutralize a mine. The underpinning principle is to burn the high explosive, and to attempt to do so without causing a detonation. High explosives are fuels that carry their own oxygen: once they start to burn, the process is self-sustaining. By its nature, burning generates heat as it transforms the explosive from its solid form into hot gas. However, high temperature is associated with high pressure; thus, if the burning takes place inside a closed vessel, the pressure will increase, which causes the temperature to increase further, leading to even greater pressure, and so on. This positive feedback mechanism, sometime called a thermal runaway reaction, can cause the remaining solid explosive to detonate. A hole in the combustion vessel allows the hot gas to vent, limiting the build-up of the pressure and temperature.

From the above, it can be surmised that the role of an exothermic material, such as thermite, is to create a vent hole through the mine casing and then to ignite the explosive within. The main explosive charge should then combust without making the transition to detonation. However, special consideration must be given to the fuse. This mine component usually contains one or more chemical compounds that are very sensitive to heat. It is then important to consider how heat can flow towards the fuse. This can happen either due to convection of hot gas within the mine case, or due to heat conduction through metal components. Thus, the geometry of the mine, and the materials it is constructed from, must be taken into account to devise a method of attack that would allow the burning of the high explosive while minimizing the heat flow towards the fuse.

Given that the role of the thermite is simply to burn a hole through the case and ignite the explosive, it suggests that there was no real need to use large quantities of thermite with the arc star system. The process was rather wasteful. Packaging the thermite material within a container with insulation, as with the Mine incinerator, appears to make a more efficient use of the material. Furthermore, thermite is not the only exothermic material that could be used. Products such as the Thiokol flare and the British *FireAnt*TM are just as capable of delivering the heat required to burn the hole and start the explosive burning. It might even be argued that these flare provide a more efficient and safer methods given that they can be used with a greater standoff from the mine case.

What really matters with the thermal neutralization of land mines is to select of attack points around the mine case such that the heat flow towards the fuse is minimized. It is also necessary to burn as much of the explosive as possible before the fuse finally explodes. Given that the fuse is usually located near the centre of a mine, this suggests that the thermal attack must be initiated at several points around the circumference of the mine.

6. Conclusions

6.1 Thermite Products

With one exception, all target AT and AP mines were destroyed in the CIL/Evan *ArcStar* and DEW *Mine Incinerator* trials. CIL/Evan *ArcStar* burned out the explosive for 39% of the trials and DEW *Mine Incinerator* burned out the explosive for 22% of the trials. When detonation occurred, the products did reduce the quantity of explosive available at the time of detonation by some degree, although 28% with CIL/Evan *ArcStar* and 71% with DEW *Mine Incinerator* still had high order detonation. These results were extremely dependant on the test setup, trial conditions, and mine types involved.

Thermite was generally most effective in burning out mines that contained a smaller amount of explosive (AP mines) and for mines with non-metal casing materials such as Bakelite. Thermite was particularly ineffective against all mines that contained a

significant amount of metal (M15, M21 and M16A2) as they detonated in all cases. The trial data also showed that multiple entry points, moisture sources and heat barriers might be helpful, but these trends were not always consistent. The heat calculations performed indicate that the use of thermite to neutralize buried mines is inefficient due to the huge heat loss to the soil layer between the mine and the thermite. This conclusion is further supported by the fact that this process is unreliable and does not provide demining personnel with any assurance that the mine has been completely neutralized. The thermite would work faster with an exposed metal-cased mine than an exposed plastic mine, thereby reducing the amount of heat lost to the atmosphere and soil. The trials, however, indicate better results with plastic mines and for mines with a smaller amount of explosive. This might be due to the larger thermite mass to explosive mass ratio.

Results with the pre-packaged *Mine Incinerator* thermite were fairly consistent, but those with the *Arc Star* thermite were not, which implies that the thermite set-up geometry is important to obtain consistent results. This creates implications for use in the field since military or humanitarian deminers would need to develop an attack mode tailored to each mine type to obtain a high probability of positive burnouts. A good training program and detailed Standard Operating Procedures (SOPs) for use would be essential, which would in turn require further comprehensive testing to investigate the best method and location of thermite application.

It is evident, especially in light of the variability of the results, that both the geometry of the mine and the materials used in its construction play a pivotal role in determining the effectiveness of the thermite products. Both must be considered when devising a method of attack that will ensure that the explosives will burn yet will still minimize heat flow toward the fuse.

The use of thermite for general destruction of in situ mines and UXO has a high risk of mine detonation for many mine types. It follows that standard safety distances for explosives [8] would have to be observed during the use of thermite. The risk of damage to surrounding infrastructure and terrain from fire or detonation is high, and potential damage may be higher because of the spewing molten metal that can easily be scattered up to 100m in the process. Scattering metal would be detrimental to the false alarm rate during mine detection operations in the rest of the minefield if a destruction must be done in situ. The combination of these factors would require that thermite be used in a safe area, such as a demolition pit or quarry. Thermite could possibly be useful in the role of destroying bulk-removed mines or UXO, as the fuse would no longer be present. Such destruction would still require measures to prevent the scatter of molten metal, mine debris and explosive remnants in the event of a detonation. The primary advantage of using thermite is that it is not an explosive. The transport, storage and handling requirements for thermite are much less stringent than those required for explosives. In certain cases, explosives cannot be safely delivered to the demining site, nor can they be safely stored or properly secured. In cases where explosives are available, thermite could be an option for the destruction of mines and UXO.

There are other exothermic materials available, such as the Thiokol flare and the British *Fire Ant*TM, which may be useful in demining operations.

6.2 Numerical Model

The numerical model presented in the report provided a simple one-dimensional representation of the heat loss. However, there are several limitations to this model, the most significant being its physical geometry. A two-dimensional spatial model would more accurately represent the placement of thermite in a trench around the perimeter of the mine. The third dimension in such a model would be time. To accurately model focusing containers, the addition of a third spatial dimension (azimuthal direction) would be required.

Additionally, in the current model, the thermite temperature is fixed at 2857 °C. In reality, this value should decrease as the products of the reaction cool prior to the onset of TNT combustion. Recommended simulations could begin with all the thermite fully reacted and at a temperature of 2857 °C. After this initiation, the thermite should be allowed to cool via conduction to the soil, conduction to the mine, radiation to the environment, and natural convection to the environment. The heat loss to the atmosphere via conduction and radiation should account for the change in surface temperature of the thermite with time. Two conditions should be monitored during the simulations: the melting temperature of the mine's casing and the ignition temperature of TNT. The time at which either of these conditions is met should cause the simulation to stop since the mine would be considered to be in the state of combustion. Such a model could be developed in either Excel, with Visual Basic for Applications (VBA), or in Matlab. Visual Basic could be used to store the two-dimensional spatial array information from one time step to the next, facilitating the use of Excel problems with array dimensions greater than two. Multi-dimensional arrays are easily handled in Matlab but it has a much smaller user base and is a more expensive software package.

7. References

1. Fuhrer, O. (2000). Inverse Heat Conduction in Soils. (Online) Institute for Atmospheric and Climate Science. <http://iacweb.ethz.ch/staff/fuhrer/publ/dipl/>.
2. Avallone, E.A., Baumeister III, T. (1996). *Mark's Standard Handbook for Mechanical Engineers*, 10th Edition. McGraw Hill, Toronto.
3. Author unknown. (n.d.) Material Property Data. (Online). MatWeb. <http://www.matweb.com>.
4. Meyer, R. (1981). *Explosives*, 2nd Edition, Verlag Chemie GmbH.
5. Holman, J.P. (1997). *Heat Transfer*, 8th Edition. McGraw Hill, United States.
6. Department of National Defence. (2004). Canadian Forces Landmine Database. (Online) National Defence Mine/Countermine Information Centre. <http://ndmic-cidnm.forces.gc.ca/>.
7. Barchard, J., Küpper, A. (2004). *DRDC Soil Laboratory Program – Triaxial Test Results – Onager Site*. DRDC Suffield CR 2004-138. AMEC Earth and Environmental Ltd., Edmonton, Alberta.
8. Author unknown. (2004). Recommended Methods for the Destruction of Explosives and Accessories. (Online) Irish Industrial Explosives Ltd. http://www.iie-online.com/pdfs/Reccomended_Methods.pdf.
9. Özisik, M.N. (1993). *Heat Conduction*, 2nd Edition. Wiley and Sons, n.p.

Annex A – Numerical Method for Transient Heat Conduction

The method outlined here was obtained from M.N. Özisik, *Heat Conduction*, 2nd Edition, Wiley and Sons, 1993.

The analytical heat equation for one-dimensional conduction is as shown below:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$

where

T = temperature of the solid [K]

x = dimension along direction of heat transfer [m]

α = thermal diffusivity [m²/s]

The above equation can be solved numerically by dividing the total length and time considered for heat transfer into a finite number of elements. The Euler approximation of this differential equation is as follows:

$$T_m^i = rT_{m-1}^{i-1} + T_{m+1}^{i-1} + (1 - 2r)T_m^{i-1}$$

where,

i = number of the timestep

m = nodal location

T = Temperature of the spatial node at the time indicated by i [K]

$r = \frac{\alpha \cdot \Delta t}{\Delta x^2}$; should be < 0.5 for convergence of numerical solution

Δt = timestep [s]

Δx = length element [m]

α = thermal diffusivity [m²/s]

The above equations were evaluated using the computational software, Matlab® Version 5.3, with the following initial conditions and boundary conditions:

Initial temperature, $T_m^0 = 25^\circ C$

Surface temperature, $T_M^i = 2857^\circ C$

Where, 2857 °C is the flame temperature of thermite and M is the nodal location at the surface in contact with the thermite

For the buried mine, it was assumed that the temperature of the casing at the soil/casing interface was the same as the temperature of the soil at the same interface.

The plots obtained are shown in Figures 4 through 7 in Section 3.1.

These plots illustrate the change in temperature distribution along the soil and/or casing thickness with time. The total time interval for which the computations were performed was adjusted until the inner surface of the casing ($x = 0$) reached the auto-ignition temperature of the explosive (333 °C for TNT). The temperature gradient at the thermite/soil (for the buried mine) and thermite/casing (for the exposed mine) was used to calculate the heat transfer rate at a particular time using the following equation:

$$q^i = k \cdot \Delta x \frac{\Delta T}{\Delta t}$$

$$q^i = k \cdot \Delta x \frac{T_{\text{thermite}} - T_{M-1}^i}{\Delta t}$$

where,

q^i = rate of heat transfer over timestep i [W]

T_{thermite} = temperature of thermite [°C] = flame temperature of thermite = 2857 °C

$M-1$ = node location just beside the interface with thermite

In this manner, the discrete values of temperature at two nodes, the node at the surface and the next node, are used to calculate the heat transfer rate over any particular timestep.

The plots of heat transfer rate vs. time, thus obtained, are shown in Figures 8 through 11 in Section 3.1.

These values for heat transfer rates were numerically integrated over the appropriate time interval to determine the total amount of heat transfer as shown below:

$$Q = \sum_j q^i \cdot \Delta t$$

where,

Q = total heat transferred [J] in the appropriate time interval t_{total}

$j = t_{\text{total}}/\Delta t$ = number of timesteps in t_{total}

The appropriate time was determined by the amount of time required for the inner surface of the casing to reach the auto-ignition temperature of the explosive (333 °C for TNT).

The results from these calculations, consisting of the time interval and the total heat transfer are summarized in Table 3 in Section 3.1.

A sample code used to perform these calculations for the buried mine with steel casing is included in the following pages. Similar code was used for the other cases considered. The important numerical computational parameters used in the code are recorded below in Table 11.

Table 11. Parameters for Numerical Computation of Heat Conduction into Mine

MINE CONFIGURATION	CASING TYPE	TIMESTEP, dt [s]	INCREMENTAL DISTANCE, dx [m]	TIME FOR NODE x=0 TO REACH 333 °C ± 5 °C
Buried Mine	Steel Casing	0.001	0.0005	133.50
	Plastic Casing	0.01	0.0005	1056.00
Exposed Mine	Steel Casing	0.000001	0.00001	0.03
	Plastic Casing	0.01	0.0001	162.75

Sample Code:

% File Name: Main.m

```

timestep = 0.001; % [seconds]
max_time = 150; % [seconds]
[T, x, q] = trans(timestep, max_time);
% T = temperature distribution along x
% x = length of the single/composite material
% q = heat transfer rate at surface

%Temperature Distributions
n = size(T)
time_array = [0:timestep:max_time];

last_timestep = round(n(1)); % number of timesteps in total time
considered (max_time)
maxtime75 = round(n(1) * 0.75); % number of timesteps in 75% of
total time
maxtime50 = round(n(1) * 0.5); % number of timesteps in 50% of
total time
initial = 1;

% Temperature distribution as a function of time
figure(1)
plot(x, T(initial,:), '*', x, T(maxtime50,:), '*', x,
T(maxtime75,:), '*', x, T(last_timestep,:), '*')
title('Temperature Distribution for Steel-cased Buried Mine')
xlabel('x-position [m]')
ylabel('Temperature [degrees C]')

% Temperature of surface farthest from heat source - to estimate
determine how much time is
% required to heat it to auto ignition temperature of TNT (333
degrees C)

```

```

'Temperature at 50% of total time'
T(maxtime50,1)
'Temperature at 75% of total time'
T(maxtime75,1)
'Temperature at end of time period'
T(n(1),1)

% Heat transfer rate at the surface as a function of time
figure(2)
plot(time_array, q, '*')
title('Heat Transfer Rate for Steel-cased Buried Mine')
xlabel('Time [s]')
ylabel('Rate of heat transfer,q [W]')

% File Name: trans.m

function [T,x,q] = trans(dt, tmax)

%
% Function performing Euler integration of heat equation
%
dx = 0.0005

%Soil Layer
alpha1 = 6.5e-07;
k1=1.3;
L1 = 0.025;
% r1 < 0.5 for convergence of numerical solution
r1 = alpha1 * dt / (dx*dx)

% Casing Layer
% Steel Casing
rho2 = 7850; % density [kg/m^3]
cp2 = 418; % specific heat [J/kg/K]
k2 = 51.9; % thermal conductivity [W/m/K]
L2 = 0.002; % thickness [m]
alpha2 = k2 / (rho2 * cp2);
r2 = alpha2 * dt / (dx*dx) % r2 < 0.5 for convergence of numerical
solution

L = L1 + L2;
T_initial = 25;
T_surface = 2857;

xstart1 = L2 + dx

x1 = [xstart1:dx:L];
x2 = [0:dx:L2];
x = [0:dx:L];
t = [0:dt:tmax];
M = length(x)
M1 = length(x1)

```

```

M2 = length(x2)
I = length(t);

T = zeros(I,M);
q = zeros(I,1);
totalq = 0;

%
% T (time, space)
% T (I, M)
%
for i = 1:M
    T(1, i) = T_initial;
end

for i = 2:I
    T(i, M) = T_surface;
end

for i = 2:I
    for m = M2:M-1 % temperatures in the soil layer
        T(i,m)=r1*(T(i-1,m-1)+T(i-1,m+1))+(1-2*r1)*T(i-1,m);
    end
    for m = 2:M2-1 % temperatures in the casing layer
        T(i,m)=r2*(T(i-1,m-1)+T(i-1,m+1))+(1-2*r2)*T(i-1,m);
    end
    T(i,1) = T(i,2);
    q(i) = k1*dx*(T_surface-T(i, (M - 1))); % 1-D conduction equation
    totalq = totalq + q(i)*dt;
end

'total heat transfer'
totaltime = round(I*.89); % time taken for the node at x=0 to reach
auto ignition temperature of TNT (333 degrees C)
for j = 1:totaltime
    q(i) = k1*dx*(T_surface-T(i, (M - 1)));
    totalq = totalq + q(i)*dt;
end

totalq % total heat transferred in the given time period [J]

```

Annex B – Heat Conduction Properties of Soil

The heat transfer properties of soil depend on a number of factors including soil composition, moisture content, depth of soil and so on. There are several analytical as well as empirical solutions to model heat conduction in different types of soils. Fuhrer [1] discusses these methods but does not address heat transfer by radiation and convection, which is negligible at most times. Convection is significant only when there is rapid infiltration of water, and radiation is significant only in “dry soils at high temperatures and within large pores” [1].

For coarse soils with moisture content greater than $0.03 \text{ m}^3/\text{m}^3$ and fine soils with moisture content less than $0.05\text{-}0.1 \text{ m}^3/\text{m}^3$, the De Vries model can be applied to approximate within $\pm 10\%$ the “macroscopic thermal conductivity of ellipsoidal soil particles in a continuous medium of water or air”. [1] The following figures show data collected and recorded for a sandy loam soil at Research Centre Foulum, Denmark [1].

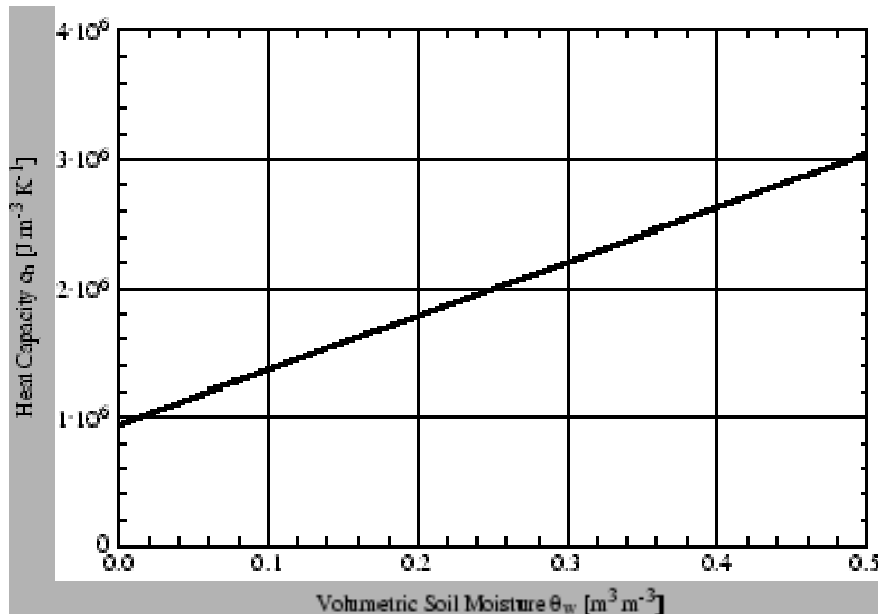


Figure 14. Heat Capacity of Sandy Loam Soil (Upper 5cm-15cm Layer)

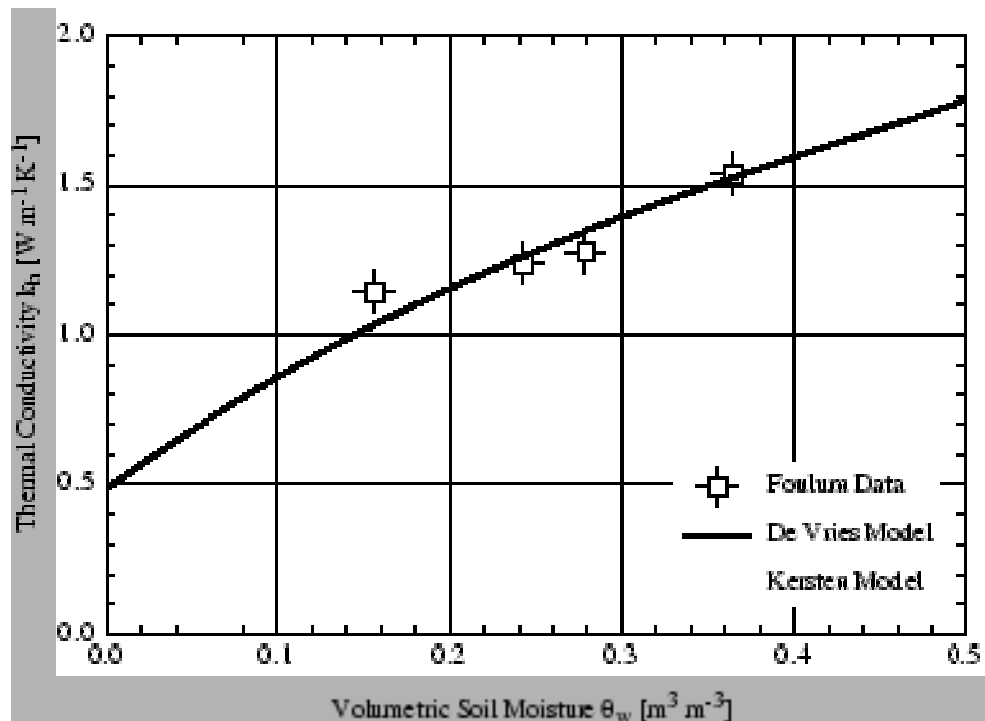


Figure 15. Thermal Conductivity of Sandy Loam Soil (5-10cm from Surface)

The thermite trials at DRDC Suffield were conducted on prairie soil. However, landmines are encountered in a wide variety of soils and it is difficult to perform heat transfer calculations that are representative of all possible soil types. Fuhrer's readily available data for sandy loam soil (Figures 14 and 15) is used for the heat calculations presented in this report. The thermal properties were obtained from the above graphs for a volumetric soil moisture of $0.25 \text{ m}^3/\text{m}^3$. The specific heat was determined as $2.0 \times 10^6 \text{ W/m}^2.\text{K}$ and the thermal conductivity was taken as 1.3 W/m.K .

Annex C – Mines Used in Thermite Trials

The following excerpts from the Canadian Forces Landmine Database provide details regarding the mines used in the thermite trials at DRDC Suffield.

M15

Mine Type:	Anti-tank
Country of Origin:	United States of America
Mine Action:	Pressure Actuated Blast
Material:	Steel
Shape:	Circular
Colour:	Green, Olive

Weight (grams):	14270
Explosive Content:	10.33 kg of Composition B plus an 11 g RDX booster
Length (mm):	N/A
Width (mm):	N/A
Height (mm):	125
Diameter (mm):	337



Figure 16. M15 – Photo

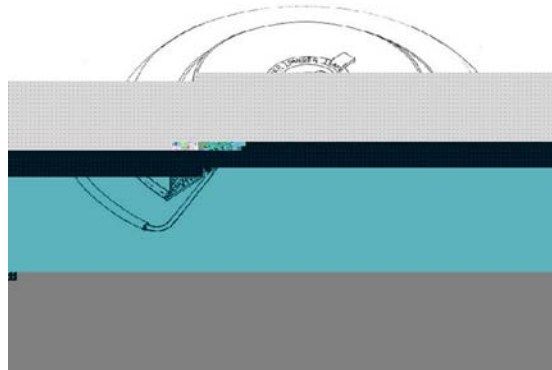


Figure 17. M15 – Line Drawing

Countries Found In: Afghanistan, Angola, Belgium, Burundi, Cambodia, Canada, Chile, Cuba, Cyprus, Democratic Republic of Congo, Eritrea, Ethiopia, Korea, Lebanon, Rwanda, Somalia, Sudan, United States of America, Western Sahara, Yemen, Zambia

Mine Description: The M15 is a circular, steel bodied AT mine which is designed to damage or destroy vehicles by blast effect. The bottom of the mine is crimped to the upper part and the mine body has a rounded upper edge. The top of the

mine is taken up by a large diameter pressure plate which has a stepped appearance. In the center of the pressure plate is a fuse cavity cap which has an arming dial and a three position selector marked "SAFE", "DANGER" and "ARMED" on the caps edges. The M15 has two anti-disturbance fuse cavities, one on the side and one on the bottom. It also has a folding metal carrying handle mounted on the bottom. The M15 can be located using metal detectors under most field conditions and can be defeated by blast overpressure clearance systems such as the Giant Viper and MICLIC. The American M6 AT mine looks almost identical but is shorter in height and contains 5 kg less explosive than the M15.

Mine Operation: A force of 135 kg on the pressure plate overcomes spring resistance and presses down on the M603 pressure fuse. Pressure inverts the Belleville spring inside the fuse causing it to snap into reverse and strike the primer which ignites and sends a spark into the detonator which begins the explosive chain.

Hazards: The M15 can be located easily using metal detectors or prodding under most field conditions. The mine can be equipped with two anti-disturbance fuses, normally the M1 pull or the M5 (mouse trap) pressure release. In some mines the M603 fuse is replaced with a M608 double impulse fuse that is resistant to mine roller breaching and blast overpressure from explosive breaching systems like Giant Viper and MICLIC. On detonation, the mine will normally cause a mobility kill on the vehicle as well as propel secondary fragmentation out to a radius of 150 to 225 meters based on the following formula [cube root of explosive weight in kg x 2.2 x 100 meters] for safe fragmentation radius.

Detection Methods

Sight:	No
Metallic Mine:	Yes/Easy
Prodding:	Yes
Non-Metallic Mine:	Unknown
Dog:	Yes
Infrared:	Unknown

Safely Approachable: The M15 has conventional pressure fusing. It is a blast mine with high metal content which can be laid mechanically or by hand. Observe standard AT drills

Clearing Methods

Hand:	Yes
Explosive Methods:	Yes
Mine Plow:	Yes
Mine Roller:	Yes

M21

Mine Type: Anti-tank
Country of Origin: United States of America
Mine Action: Tilt-Rod or Pressure Actuated Penetrator
Material: Steel
Shape: Circular
Colour: Green, Olive

Weight (grams): 7900
Explosive Content: 5 kg of H6
Length (mm): N/A
Width (mm): N/A
Height (mm): 813
Diameter (mm): 230

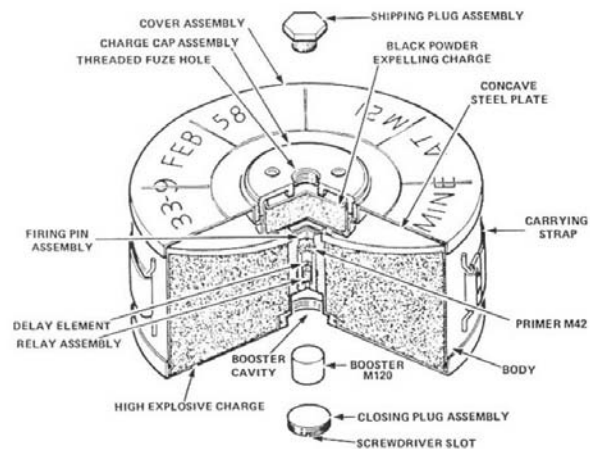


Figure 18. M21 – Photo

Figure 19. M21 – Line Drawing

Countries Found In: Canada, Cyprus, Iraq, Kuwait, United States of America

Mine Description: The M21 is a circular, steel bodied, AT mine which is designed to damage or destroy vehicles by a penetrating effect. The bottom of the mine is crimped to the upper mine body. An adjustable, cloth carrying handle is attached to the side of the mine body and a large filler plug is positioned between the handle connection points. A booster well is centered on the bottom. The mine has a small diameter fuze cavity and a stamped radial pattern centered on top. The mine is almost always fitted with an M607 tilt rod fuse which can be detected visually; the mine is also detectable using metal detectors. Other fuses available include the M612 pneumatic fuse and the M609 influence fuse. When the tilt rod or pneumatic fuses are used, the M21 can be defeated by blast overpressure clearance devices such as the Giant Viper and MICLIC.

Mine Operation: Tilt Rod - 1.7 kg of lateral force tilt the rod through 20' and break the plastic stabilizing collar on the fuse. The tilt-rod then presses against the bearing cap forcing it down onto a Belleville spring which inverts and snaps the firing pin down onto a M46 detonator. The detonator initiates a black powder charge which blows the top cover off the mine and drives a firing pin into a M42 primer. This initiates the explosive chain and fires a machined steel plate up into the bottom of the target. Pressure - 132 kg of pressure initiates the same sequence as the tilt-rod.

Hazards: The M21 has no unusual detection hazards. If the mine is being pulled ensure that a 90' turn is used in your pulling rope so that the force of the explosion doesn't come at you if the mine goes off.

Detection Methods

Sight:	Yes/Tiltrod
Metallic Mine:	Yes/Easy
Prodding:	Yes
Non-Metallic Mine:	Unknown
Dog:	Yes
Infrared:	Unknown

Safely Approachable: The M21 has conventional pressure/tilt-rod fusing. It is a hand laid penetrating mine with high metal content. Observe standard AT drills.

Clearing Methods

Hand:	Yes
Explosive Methods:	Yes
Mine Plow:	Yes
Mine Roller:	Yes

M16A2

Mine Type:	Anti-personnel
Country of Origin:	United States of America
Mine Action:	Pull/Pressure-Actuated Bounding Fragmentation
Material:	Steel
Shape:	Cylindrical
Colour:	Green, Olive
Weight (grams):	2830
Explosive Content:	590 g of TNT plus an 11 g booster of Comp A5
Length (mm):	N/A
Width (mm):	N/A
Height (mm):	199
Diameter (mm):	103

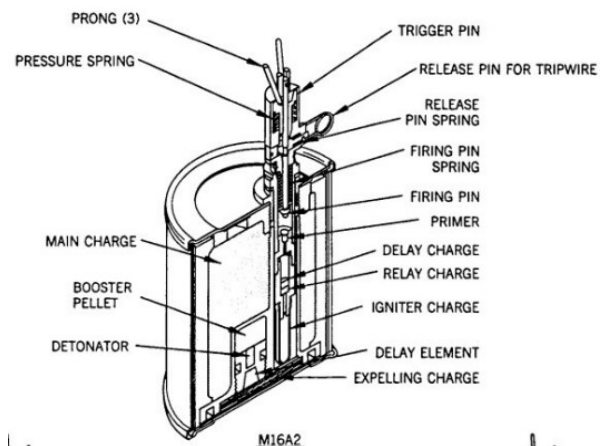


Figure 20. M16A2 – Photo

Figure 21. M16A2 – Line Drawing

Mine Description: The M16A2 is a cylindrical, steel bodied, bounding AP mine which is designed to wound or kill by fragmentation. The mine resembles a large tin can, it has a crimped upper edge and a threaded fuse cavity offset from center on top of the body. A tubular, pronged fuse (M605 pull/pressure) is screwed into the cavity and the mine is ready for use. Pull of 1.5 kg on a tripwire or pressure of 3.5 kg on one of three prongs on top of the M605 actuates the mine. When actuated, the mine bounds approximately 1.5 meters into the air and explodes, scattering fragmentation to a radius of 30 meters. The mine has an emplaced life expectancy (70% chance of functioning as designed) of 8 years in temperate zones with clay soil, and up to 12 years in a tropical environment. The M16 series of bounding mines can be located visually or with metal detectors under most field conditions. All M16 series mines can be defeated by blast overpressure clearance methods like the Giant Viper and MICLIC. The M16A2 is the latest of the M16 series bounding mines which have been developed since the 1950's. Earlier versions include the M16 and M16A1 which are heavier and have the fuse cavity centered on top. The basic concept for bounding mines was first used by the Germans in WWII and has been widely copied.

Mine Operation: Pressure of 3.5 kg on one of the three fuse prongs or pull of 1.5 kg on a tripwire displaces the locking balls in the fuse and releases the firing pin which strikes a percussion cap. The cap initiates a pyrotechnic delay which in turn burns down the flash tube to the propelling charge. The propelling charge expels the mine body upward and simultaneously ignites a pyrotechnic delay which fires the detonator and the main charge after a 0.5 second delay.

Hazards: The M16 series of mines have a very high metal content and can be located visually as well as with prodders or metal detectors. They have no unusual hazards associated with them. On detonation, the mine will bound and normally propel lethal fragmentation to a radius between 25 and 50 meters. The actual hazard radius for these types of mines averages out at 105 meters based on the following formula [cube root of explosive weight in kg x 2.2 x 100 meters] for safe

fragmentation radius. Always be alert for pressure actuated blast mines along the tripwire (don't get tripwire fixation).

Detection Methods

Sight:	Yes/Tripwire
Metallic Mine:	Yes/Easy
Prodding:	Yes
Non-Metallic Mine:	Unknown
Dog:	Yes
Infrared:	Unknown

Safely Approachable: The M16A2 has conventional pressure/pull fusing. It is a hand laid bounding fragmentation mine. Observe standard tripwire drills.

Clearing Methods

Hand:	Yes
Explosive Methods:	Yes
Mine Plow:	Yes
Mine Roller:	Yes

PT-Mi-Ba III

Mine Type:	Anti-tank
Country of Origin:	Czech Republic
Mine Action:	Pressure Actuated Blast
Material:	Bakelite
Shape:	Circular
Colour:	Black, Brown, Olive
Weight (grams):	9900
Explosive Content:	7.2 kg of Cast TNT, 116 g booster pressed TNT.
Length (mm):	N/A
Width (mm):	N/A
Height (mm):	108
Diameter (mm):	330



Figure 22. PT-Mi-Ba III – Photo

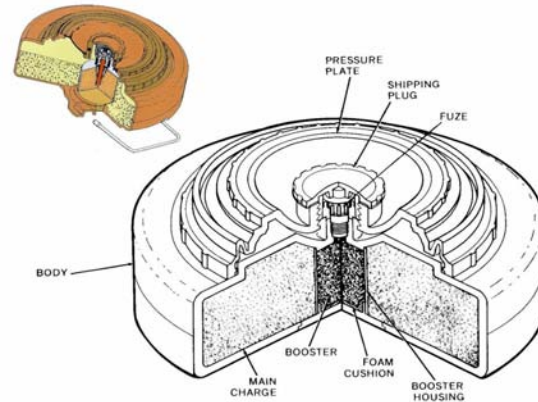


Figure 23. PT-Mi-Ba III – Line Drawing

Mine Alias: PTM-BA-III Bulgaria

Countries Found In: Angola, Burundi, Cambodia, Czech Republic, Democratic Republic of Congo, Eritrea, Ethiopia, Iraq, Kuwait, Lebanon, Mozambique, Namibia, Poland, Rwanda, Somalia, South Africa, Sudan, Zambia

Mine Description: The PT-Mi-Ba III is a circular, Bakelite-bodied AT mine which is designed to damage or destroy a vehicle by blast effect. The top of the mine has a stepped appearance, with small reinforcing ribs around the circumference of the pressure plate. A small knurled fuse cavity cap is located in a depression in the center. The bottom has a telescopic plastic carrying handle recessed into two grooves to fit flush with the mine. The Bakelite material is a shiny brown colour but some mines have been encountered painted flat olive or black. The mine contains 7.25 kg of TNT and is actuated by 200 kg of The PT-Mi-Ba III contains only 2.46 g of metal and it is very difficult to locate using metal detectors under most field conditions. The mine is highly resistant to blast overpressure from explosive breaching systems such as the Giant Viper and MICLIC. The mine is also produced in Bulgaria as the PTM-BA-III

Mine Operation: Pressure of 200 kg on top of the PT-Mi-Ba III will cause the pressure plate to collapse at the flexible rubber gasket. The force is then transferred onto the fuse head of the RO7 series fuse. Pressure from the fuse head breaks a shear ring inside the fuse and releases a spring-loaded firing pin to snap onto the detonator and function the mine. The RO7 fuses have interchangeable detonators which are colour-coded and have pyrotechnic firing delays of 0,2,4,6 and 8 seconds. The purpose of the firing delays is to defeat vehicles equipped with mine rollers or plows. The RO7-III is a special anti-removal fuse that will actuate the mine if any attempt is made to remove it from the fuse cavity.

Hazards: The PT-Mi-Ba III is very difficult to locate using metal mine detectors under field conditions where the ground has high metal content or where fragmentation from artillery, etc., is present. The mine has no secondary fuse cavity but the Ro-4 fuse pressure fuse has a built-in anti-disturbance feature once armed. On

detonation, the mine will normally cause a mobility kill on the vehicle as well as propel secondary fragmentation out to a radius of 150 to 225 meters based on the following formula [cube root of explosive weight in kg x 2.2 x 100 meters] for safe fragmentation radius.

Detection Methods

Sight:	No
Metallic Mine:	Yes/Very Difficult
Prodding:	Yes
Non-Metallic Mine:	Unknown
Dog:	Yes
Infrared:	Unknown

Safely Approachable: The PT-Mi-Ba III has conventional pressure fusing. It is a blast mine with low metal content and it can be laid mechanically or by hand. Observe standard AT drills.

Clearing Methods

Hand:	Yes
Explosive Methods:	Yes
Mine Plow:	Yes
Mine Roller:	Yes

PP-Mi-Na 1

Mine Type:	Anti-personnel
Country of Origin:	Czech Republic
Mine Action:	Pressure Actuated Blast
Material:	Plastic
Shape:	Square
Colour:	Green, Olive
Weight (grams):	175
Explosive Content:	93 g of TNT
Length (mm):	91.5
Width (mm):	71.5
Height (mm):	47
Diameter (mm):	N/A



Figure 24. PP-Mi-Na-1 – Photo

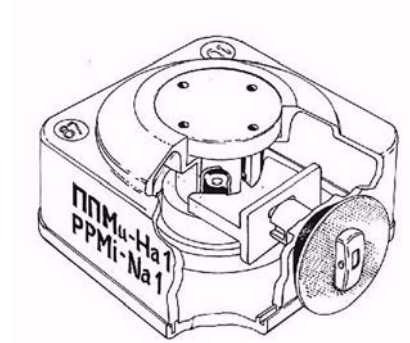


Figure 25. PP-Mi-Na-1 – Line Drawing

Countries Found In: Czech Republic, Slovakia

Mine Description: The PP-Mi-Na 1 is a square, plastic bodied scatterable AP mine which is designed to wound or kill by blast effect. The mine is molded from green plastic, with rounded corners and large circular areas on the top and bottom which appear to be pressure plates. The mine also has a large bell shaped arming handle on the side. The PP-Mi-Na 1 was designed for quick mechanical laying from vehicles such as, the VZ-92 minelayer and scattering helicopters but it can also be laid manually. The mine has a very low metal content (firing pin and spring) and is very difficult to locate using metal detectors under most field conditions. The mine may have a limited resistance to blast overpressure from explosive breaching systems like the Giant Viper and MICLIC.

Mine Operation: The PP-Mi-Na 1 is actuated by pressure. Force on either the top or bottom pressure plate releases a spring-loaded firing pin to snap onto a percussion cap/detonator and begin the explosive chain.

Hazards: The PP-MI-Na 1 can be scatter laid and the area will most likely be unmarked. When buried it is difficult to locate using metal detectors where the ground has high metal content or fragmentation is present. In good conditions, such as sand, the mine can be located using the AN-19/2 metal detector. On detonation, the mine will cause immediate blast injury to the victim as well as hearing damage to anyone within a 5-meter radius. It will also propel secondary fragmentation to a radius of 25 to 100 meters.

Detection Methods

Sight:	Yes/Scatterable
Metallic Mine:	No
Prodding:	Yes
Non-Metallic Mine:	Unknown
Dog:	Unknown
Infrared:	Unknown

Safely Approachable: The PP-Mi-Na 1 has conventional pressure fusing. It is a blast mine with low metal content which can be hand laid or scattered from helicopters. Observe standard AP drills.

Clearing Methods

Hand:	Yes
Explosive Methods:	Yes
Mine Plow:	Yes
Mine Roller:	Yes

Annex D – CIL/Evan Trial Details

20 May, Shot M98140A – 0.9 kg (2 Lb). Thermite vs. M15 Anti-Tank Mine. A fused and armed M15 anti-tank mine was flush-buried in the native clay soil. One pound of thermite was loosely poured in a ring around the upper perimeter edge of the mine. This charge was supplemented by a second one pound bagged charge of thermite (Figure 26). Burn-through occurred at the bagged charge location approximately 15 seconds after ignition. The mine burned intensely for 3 minutes and 34 seconds, at which point it detonated, spewing molten metal over a large radius (estimated 50-100 m). The resultant crater was 1.3 m wide by 0.5 m deep (Figure 27). Based on past cratering experience, and based on video analysis, it is estimated that 3–5 kg of explosive remained at the time of detonation.



Figure 26. 0.9 kg (2 lb) of Thermite vs. M15 Anti-tank Mine



Figure 27. *Crater from M15 Mine Detonation*

20 May, Shot M98140B – 0.5 kg (1 Lb) Thermite vs. M16A2 Anti-Personnel Mine. A single 0.5 kg (1lb) bag of thermite was placed on top, beside the fuse of a buried, armed M16A2 anti-personnel mine (Figure 28). Burn-through of the mine case occurred at the 24-second mark after ignition. The mine's bounce propellant activated at 2 minutes and 31 seconds. The mine detonated at a height of 2–3 m.



Figure 28. *0.5 kg (1 lb) of Thermite vs. an M16A2 Anti-personnel Mine – the M16A2 container remained buried in the ground*

21 May, Shot M98141A – 0.5 kg (1 Lb) Thermite vs. PP– Mi- Na-1 Anti-Personnel Mine. A single 0.5 kg (1lb) bag of thermite was placed in a small crater (Figure 29) on one side of the flush buried mine. Burn-through occurred almost immediately. The fuse activated at 2 minutes and 16 seconds. It is estimated that very

little explosive was left at the time of fuse activation, as the ring of slag left by the burn was not broken nor moved by the explosion (Figure 30).



Figure 29. 0.5 kg (1 lb) of Thermite vs. PP-Mi-Na1 Anti-personnel Mine prior to filling the hole so the mine was flush buried



Figure 30. Burned out PP-Mi-Na1 Mine Shell – slag leftover from molten metal can be seen

21 May, Shot M98141B – 0.5 kg (1 Lb) Thermite vs. PT-Mi-Ba III Anti-Tank Mine. A single, 0.5 kg (1 lb) bag of thermite was placed on top of the fused and armed Pt-Mi-Ba III mine fuse well (Figure 31). The fuse well remained exposed. Burn-through did not occur, leaving the mine intact. The molten iron had simply flowed around the groove on top of the mine and cooled off. This mine was destroyed later

using a standard explosive demolition technique. The mine completely burned out after approximately 33 minutes (Figure 32).



Figure 31. 0.5 kg (1 lb) of Thermite vs. PT-Mi-Ba III Anti-tank Mine

21 May, Shot M98141C – 0.9 kg (2 lb) Thermite vs. M15 Anti-Tank Mine. One pound of thermite was poured in a complete ring around the mines upper rim, plus a single bag (Figure 33). Burn-through occurred at 9 seconds at the bag's location and at 39 seconds at a second, opposite location. The fuse activated at 7 minutes, spewing molten fragments over a 20 m radius. Most of the metal case remained in the hole in the ground (Figure 34).



Figure 33. 0.9 kg (2 lb) of Thermite vs. M15 Anti-tank Mine



Figure 34. Crater from M15 Anti-tank Mine Detonation

21 May, Shot M98141D – 0.9 kg (2 lb) Thermite vs. M16A2. Two pounds of thermite were placed in a cup, covered by a single sheet of wet paper towel, beside a flush buried, fused M16A2 (Figure 35). The cup had a taped over hole in the bottom side closest to the mine, to ensure the molten mass streamed towards the mine. Burn-through occurred at 9 seconds. The burn continued till 10 minutes and 40 seconds when the fuse activated. The mine continued to burn for several minutes after that, leaving an empty shell (Figure 36).



Figure 35. 0.9 kg (2 lb) of Thermite vs. M16A2 Anti-Personnel Mine



Figure 36. Empty M16A2 Casing After Mine Activation.

22 May, Shot M98142A – 0.5 kg (1 lb) Thermite vs. PP-Mi-Na1. One pound of thermite was poured into a prepared paper dam around the top of the fused, armed, and partially buried mine (Figure 37). Two sheets of wet paper towel covered the dam. Burn-through was at 11 seconds. The fuse activated at 55 seconds. The mine was completely burned out at 9 minutes and 11 seconds (Figure 38).



Figure 37. 0.5 kg (1 lb) of Thermite vs. PP-Mi-Na1 Anti-personnel Mine



Figure 38. *Burned out PP-Mi-Na1 Mine Case*

22 May, Shot M98142B – 3 kg (6 lb) Thermite vs. M15. Four pounds of loose thermite were poured in a ring around the partially exposed mine, and two one pound cups were placed on opposite sides of the mine (39). Burn-through occurred at 6 seconds. The fuse activated at 4 minutes and 10 seconds, but the amount of high explosive left was negligible. (Figure 40).



Figure 39. *3 kg (6 lb) of Thermite vs. M15*



Figure 40. Burned out M15 mine case

22 May, Shot M98142C – 3 kg (6 lb) vs. PT-Mi-Ba III. Four pounds of loose thermite were poured in a ring around the mine, and two one pound cups were placed on opposite sides of the mine's upper surface (Figure 41). Burn-through occurred at 1 minute and 6 seconds. The mine was completely burnt out without any high order detonation after approximately 30 minutes.



Figure 41. 3 kg (6 lb) of Thermite vs. PT-Mi-Ba III



Figure 42. *Burned out Pt-Mi-Ba III Mine Case*

22 May, Shot M98142D – 5.0 kg (11 lb) vs. PT-Mi-Ba III. Seven pounds of loose thermite were poured in a ring around the mine, and four one pound cups were placed equidistant in a rectangular pattern (Figure 43). Burn-through occurred at the four cup locations, with the first occurring at 40 seconds. The fuse activated at 14 minutes and 28 seconds causing a small explosion since most of the explosive had burned (Figure 44).



Figure 43. *5.0 kg (11 lb) of Thermite vs. PT-Mi-Ba III Mine*



Figure 44. *Small Crater from PT-Mi-Ba III Mine Detonation*

25 May, Shot M98145A – 3 kg (6 lb) vs. M15. Four pounds of loose thermite and two one pound cups were used in this trial. (Figure 45). Burn-through occurred at 28 seconds, and the mine detonated at 3 minutes and 17 seconds. The resultant crater was 1.3 m by 0.5 m. It is estimated that 3 –5 kg of explosive were left at detonation. (Figure 46).



Figure 45. *3 kg (6 lb) of Thermite vs. an M15 Mine*



Figure 46. Crater from M15 Mine Detonation

25 May, Shot M98145B – 0.5 kg (1 lb) vs. PP Mi Na 1. One pound of loose thermite was poured into a cardboard, heat-retaining holder then a wet paper towel was placed over it. (Figure 47). Burn-through occurred at 53 seconds. The fuse activated at 1 minute and 59 seconds. The mine was virtually burned out at that point (Figure 48).



Figure 47. 0.5 kg (1 lb) of Thermite vs. PP-Mi-Na1 Mine



Figure 48. *Small Crater from PP-Mi-Na1 Mine Detonation*

26 May, Shot M98146A – 4 kg (8 lb) vs. PT-Mi-Ba III. Five pounds of loose thermite was poured in a ring around the mine and three more pounds were added in cups, each with a wet paper towel on top (Figure 49). Burn-through occurred at 23 seconds. The mine fuse activated at 19 minutes and 4 seconds. The small explosion did not disturb the burned out mine shell (Figure 50).



Figure 49. *4 kg (8 lb) of Thermite vs. PT-Mi-Ba III Mine*



Figure 50. Mine Casing from PT-Mi-Ba III Mine

26 May, Shot M98146B – 0.9 kg (2 lb) vs. M16A2. One pound of loose thermite was poured in a ring around the upper portion of the exposed, buried mine case. A second pound in a cup open at the bottom, with a wet paper towel on top, was placed beside the mine. (Figure 51). Burn-through occurred at 1 minute and 26 seconds. The fuse activated at 2 minutes and 56 seconds. The mine finished burning out at 4 minutes and 56 seconds (Figure 52).



Figure 51. 0.9 kg (2 lb) of Thermite vs. M16A2 Mine



Figure 52. Burned out M16A2 Mine Case

26 May, Shot M98146C – 1.1 kg (2.5 lb) vs. M16A2. Set up as in Shot M98146B, with 1.5 pounds of loose thermite (Figure 53). Burn-through occurred at 32 seconds. The mine fuse activated, and the mine jump/detonation functioned normally at 3 minutes and 33 seconds (Figure 54).



Figure 53. 1.1 kg (2.5 lb) of Thermite vs. M16A2 Mine



Figure 54. Mine Casing Ejected from M16A2 Mine

1 June, Shot M98152A – 2 kg (5 lb) vs. M21 Anti-Tank Mine. Three pounds of loose thermite were poured in a ring around the mine, and two one pound cups with a wet paper towel on each were added (Figure 55). Burn-through occurred at 6 seconds. The fuse activated at 35 seconds, but did not detonate the mine. The mine was completely burned out by 2 minutes and 30 seconds (Figure 56). The fuse activated after 35 seconds and burning continued for 2 minutes. Upon inspection after the trial, it was found that the main charge had been broken in several large pieces that were dispersed on the site and were still intact.



Figure 55. 2 kg (5 lb) of Thermite vs. M21 Anti-tank Mine



Figure 56. *Burned out M21 Mine Casing*

1 June, Shot M98152B – 2 kg (5 lb) vs. M21. The set-up was a repeat of 16 (Figure 57). Burn-through occurred at 5 seconds. The fuse activated at 18 seconds ejecting a piece of the main charge, but did not detonate the mine. The remainder of the mine was completely burned out by 1 minute and 33 seconds (Figure 58).



Figure 57. *2 kg (5 lb) of Thermite vs. M21 Mine*



Figure 58. Burned out M21 Mine Casing

1 June, Shot M98152C – 2 kg (5 lb) vs. M21. Set-up was as per 16 and 17 (Figure 59). Burn-through occurred at 6 seconds. The mine fuse activated at 1 minute and 5 seconds and the mine detonated. The resultant crater was 1 m by 0.7 m (Figure 60). It is estimated that 2–3 kg of explosive remained at the time of detonation.



Figure 59. 2 kg (5 lb) of Thermite vs. M21 Mine



Figure 60. *Crater from M21 Detonation*

Table 12. CIL/Evan Trial Data (page 1 of 3)

DATE	SHOT ID (VIDEO ID)	MINE/ TYPE	THERMITE USED			TIMINGS			EFFECTS	COMMENTS
			LOOSE	CONTAIN	TOTAL	BURN THROUGH	FUSE DET.	MINE DET.		
20 May	M98140A (V 8)	M15 / AT	0.5 kg (1 lb)	0.5 kg (1 lb)	0.9 kg (2 lb)	15"		3' 34"	Crater 1.3 m x 0.5 m	est. 3-5 kg of expl left at time of det.
	M98140B (V 9)	M16A2/ APers	none	0.5 kg (1 lb)	0.5 kg (1 lb)	24"		2' 31"	Mine det at 2-3 m height	Normal mine function
21 May	M98141A (V 10)	PPMiNa1/ APers	none	0.5 kg (1 lb)	0.5 kg (1 lb)	< 5"		2' 16"	Mine detonation	Ring of slag left
	M98141B (V 11)	PT-Mi-Ba III/ AT	none	0.5 kg (1 lb)	0.5 kg (1 lb)	N/A		no	No effect, mine intact	Mine demolition required
	M98141C (V 12)	M15/ AT	0.5 kg (1 lb)	0.5 kg (1 lb)	0.9 kg (2 lb)	9" & 39"	7"	6' 01"	Crater 0.7m x 0.2m	Est. 1-2kg of expl. Left at time of detonation
	M98141D (V 13)	M16A2/ APers	0.5 kg (1 lb)	0.5 kg (1 lb)	0.9 kg (2 lb)	1' 9"	10' 40"	No	Burn continued after fuse det.	
22 May	M98142A (V 14)	PPMiNa1/ APers	0.5 kg (1 lb)	none	0.5 kg (1 lb)	11"	55"	No	Complete Burn at 9' 11"	
	M98142B (V 15)	M15/ AT	2 kg (4 lb)	2 x 0.5 kg (1lb)	3 kg (6 lb)	6"	4' 20"	4' 20"	Fuse activated at 4' 10"	Negligible explosive left at time of det.

Table 12. CIL/Evan Trial Data (page 2 of 3)

DATE	SHOT ID (VIDEO ID)	MINE/ TYPE	THERMITE USED			TIMINGS			EFFECTS	COMMENTS
			LOOSE	CONTAINER	TOTAL	BURN THROUGH	FUSE DET.	MINE DET.		
22 May	M98142C (V 16)	PT-Mi-Ba III/ AT	2 kg (4 lb)	2 x 0.5 kg (1lb)	3 kg (6 lb)	1' 6"	26' 05"	26' 05"	Complete burn	
	M98142D (V 17)	PT-Mi-Ba III/ AT	1 kg (3 lb)	4 x 0.9 kg (2lb)	5.0 kg (11 lb)	x4 40", 57", 1' 02", 1' 06"	14' 28"	14' 28"	Small crater	Very little expl (<1 kg) left at time of det.
25 May	M98145A (V 18)	M15/ AT	2 kg (4 lb)	2 x 0.5 kg (1 lb)	3 kg (6 lb)	28"	3' 17"	3' 17"	Crater 1.3 m x 0.5 m	est. 3-5 kg of expl left at time of det.
	M98145B (V 19)	PP-Mi-Na-1/ AP	0.5 kg (1 lb)	None	0.5 kg (1 lb)	53"	1" 59"	1" 59"	Tiny expl.	Very little expl left at time of det.
26 May	M98146A (V 20)	PT-Mi-Ba III/ AT	2 kg (5 lb)	3 x 0.5 kg (1 lb)	4 kg (8 lb)	23"	19' 4"	19' 4"	Small expl.	Very little expl left.
	M98146B (V 21)	M16A2/ AP	0.5 kg (1 lb)	0.5 kg (1 lb)	0.9 kg (2 lb)	1' 16"	2' 56"	No	Burned for 2' more after fuse det.	

Table 12. CIL/Evan Trial Data (page 3 of 3)

DATE	SHOT ID (VIDEO ID)	MINE/ TYPE	THERMITE USED			TIMINGS			EFFECTS	COMMENTS
			LOOSE	CONTAINER	TOTAL	BURN THROUGH	FUSE DET.	MINE DET.		
26 May	M98146C (V 22)	M16A2/ AP	0.68 kg (1.5 lb)	0.5 kg (1 lb)	1.1 kg (2.5 lb)	32"	3' 33"	3' 33"	Normal mine functioning	side burn attack
1 June	M98152A (V 23)	M21/ AT	1 kg (3 lb)	2 x 0.5 kg (1 lb)	2 kg (5 lb)	6"	35"	No	Burn out at 2' 30"	explosive broken and dispensed
	M98152B (V 24)	M21/ AT	1 kg (3 lb)	2 x 0.5 kg (1 lb)	2 kg (5 lb)	5"	18"	No	Burn out at 1' 33"	most explosive burnt
	M98152C 0	M21/ AT	1 kg (3 lb)	2 x 0.5 kg (1 lb)	2 kg (5 lb)	6"	1' 5"	1' 5"	Crater 1 m x 0.7 m	est. 2-3 kg of expl left at time of det.

Annex E – DEW Trial Data

29 June 1998, Shot M98180A – One Mine Incinerator Vs M15 Anti-Tank Mine.

One Type 3a DEW Thermite charge was placed on top of a buried (top surface exposed) M15 anti-tank mine (Figure 61). The charge was placed mid-way between the mine fuse and the outer rim of the mine. The charge was initiated electrically. It is difficult to assess from the video when the molten slug from the thermite charge breaches the mine's case. There is an immediate, intense plume of flame emitted from the Incinerator as the thermite reaction starts. There was an increase in flame brightness and magnitude at 58 seconds. This probably indicated that the mine's explosive contents were burning. The flame front from the point of initiation appeared to spread slowly around the mine body. There was no discoloration of the mine casing, except near the flame stack. At 5 minutes and 15 seconds, heavy black smoke appeared from around the fuse well. At 7 minutes and 40 seconds, the fuse plate started to glow. The mine fuse activated, and the unburned explosive contents detonated at 13 minutes and 8 seconds. A crater 1.5 m by 0.5 m was left (Figure 62). Based on the crater size and estimates of the unburned areas of the mine, it is believed that approximately 4 kg (~1/2) of the TNT contents detonated.



Figure 61. Type 3a Incinerator on an M15 Anti-tank Mine



Figure 62. *Crater from M15 Mine Detonation*

29 June 1998, Shot M98180B – One Type 3a vs. M15. Set-up as per 180A.

Burning appeared to start at 46 seconds. Burning followed a similar pattern to test 180A. The fuse activated at 14 minutes and 14 seconds. The detonation of approximately 50 % of the mine's TNT contents (estimated 10.33 kg) left a crater 1.8 m wide by 0.75 m deep.

30 June 1998, Shot M98181A – One Type 3a vs. M15. Set-up was as per 180A and B. Burning started at 32 seconds. Heavy smoke was observed coming from the fuse plate rim at 10 minutes and 27 seconds. Fuse activation and mine detonation occurred at 11 minutes and 34 seconds. A crater 2.0 m by 0.5 m was created by the estimated 4 kg of TNT.

30 June 1998, Shot M98181B – One Type 3a vs. M16A2 Anti-Personnel Mine.

One type 3a charge was placed on top of a fused M16A2 mine (Figure 63). The thermite charge was placed so that the thermal slug would burn into the mine case away from the fuse area. Burn-through occurred at 28 seconds. Smoke was observed coming from the fuse area at 1 minute and 17 seconds. The mine burned with heavy, black smoke until normal mine bounce/detonation at 4 minutes and 29 seconds.



Figure 63. Type 4 charge vs. an M16A2 mine

30 June 1998, Shot M98181C – One Type 3a Without Stand vs. M16A2. One Type 3a charge was placed directly on the exposed M16A2's upper face of the main mine body (see Figure 64). Burn-through occurred at 7 seconds. The burn proceeded as per 181B, but with faster venting and a cleaner burn (less smoke). The normal mine bounce/detonation occurred at 3 minutes and 12 seconds.



Figure 64. Type 3a Incinerator on an M16A2 Mine

30 June 1998, Shot M98181D – One Type 3a vs. PT-Mi-Ba III. One Type 3a charge with standoff was placed on the outer top portion of an exposed PT-Mi-Ba III mine (Fig 65). Burn-through appeared to occur at approximately 5 seconds, and the mine burned steadily until fuse activation at 31 minutes and 3 seconds. It is estimated that

only a very small portion of the explosive charge (< 100g) was left at the time of detonation (Fig 66).



Figure 65. Type 3a Charge on Stand on PT-Mi-Ba III Mine



Figure 66. Burnt out PT-Mi-Ba III Case

30 June 1998, Shot M98181E – Two Half Sized Charges vs. PT-Mi-Ba III. Two half sized charges without standoff were placed opposite on the outer top portions of an exposed PT-Mi-Ba III mine (Fig 67). Burn-through appeared to occur at approximately 6 seconds, and the mine burned steadily until fuse activation at 29 minutes and 35 seconds. It is estimated that only a very small portion of the explosive charge (< 100g) was left at the time of detonation (Fig 68).



Figure 67. Two Type 4 Charges on a PT-Mi-Ba III Mine



Figure 68. Burnt out Mine Case

Table 13. DEW Trial Data

DATE	SHOT ID (VID ID)	MINE/ TYPE	THERMITE UNITS USED	TIMINGS			EFFECTS	COMMENTS
				BURN THROUGH	FUSE DET.	MINE DET.		
29 June	M98180A (VID 1)	M15	1	00' 58"	13' 08"	13' 08"	Crater 1.5m x 0.5m	Approx 50% of expl left at time of det (est. 4 kg)
	M98180B (VID 2)	M15	1	00' 46"	14' 14"	14' 14"	Crater 1.8m x 0.75m	Approx 60% of expl left at time of det (est. 5 kg)
30 June	M98181A (VID 3)	M15	1	00' 32"	11' 34"	11' 34"	Crater 2.0m x 0.5m	Approx 50% of expl left at time of det (est. 4 kg)
	M98181B (VID 4)	M16A2	1	00' 08"	04' 09"	04' 10"	Normal mine bounce/det	Solid burn till fuse det
	M98181C (VID 5)	M16A2	1	00' 07"	03' 12"	03' 13"	Normal mine bounce/det	Solid burn till fuse det
	M98181D (VID 6)	PT-Mi-Ba III	1	00' 05"	31' 03"	31' 03"	Very small expl	est. less than 100g left
	M98181E (VID 7)	PT-Mi-Ba III	2 x 1/2	00' 06" 00' 15"	29' 34"	29' 35"	Very small expl	est. less than 100g left

Bibliography

- CIL/Evan Inc. (1998). Commercial Thermite Welding Data, Product Information Sheet. Quebec, Canada.
- CIL/Evan Inc. (1995). ARCSTAR MSDS Data. Quebec, Canada.
- Clausen, E. (1997). In Situ Incineration of Anti-Personnel Land Mines.
- Clausen, E., and Walker, R. (1999). Innovative Landmine Neutralization. A paper presented to the International Society of Exploration Engineers, Nashville, USA.
- DEW Engineering and Development Limited. (1998). Incinerator MSDS Data.
- Pains Wessex, Ltd. (1998). Market Research Report FIREANT Project. United Kingdom.
- McCracken, D. (1998). Cambodian Mine Action Center Field Standing Operating Procedures. Cambodian Mine Action Center.
- Solid Combustion Products Inc. (1998). Technical Instructions for the use of the Mine Incinerator.
- ZND Inc. (1996). Assessment of Self-Propagating High-Temperature Synthesis (SHS). Final report for work carried out for DND under Contract No. W7702-5-R544/01-XSG.
- Minaro, K., Nezaki, D., Okamoto, T., Takata, M. (2002). Growth Condition and Luminescence of ZnO Crystals Grown by Electric Current Heating with Thermite Reaction. In Proceedings of the 22nd Electroceramics Division Meeting of the Ceramic Society of Japan, .99-102. Kawasaki, Japan: Trans Tech Publications.
- Eastpoint Oltean Co. (1997). (Online) Polyvinyl Chloride Specification Sheet. <http://www.plasticsusa.com/pvc.html>

List of symbols/abbreviations/acronyms/initialisms

AP	Anti-Personnel
AT	Anti-Tank
A	Area
c	Heat capacity
DND	Department of National Defence
DOT	Department of Transport
DRDC	Defence Research and Development Canada
Gr	Grashof number
H	Convection heat transfer coefficient
HD	Humanitarian Demining
k	Thermal conductivity
L	Characteristic length
m	Constant for convection from isothermal surfaces
MI	Mine Incinerator
Nu	Nusselt number
Pr	Prandtl number
q	Rate of heat transfer
Q	Amount of heat transfer
R_{th}	Thermal resistance
S	Shape factor for two-dimensional conduction
SOP	Standard Operating Procedure
t	Time

T	Temperature
TNT	Trinitrotoluene
UXO	Unexploded Ordnance
α	Thermal diffusivity
β	Volume coefficient of expansion
ϵ	Emissivity
Δx	Thickness of material
σ	Stefan-Boltzmann constant
ν	Kinematic viscosity

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During the late 1990s, Defence Research and Development Canada – Suffield investigated a variety of principles and techniques to neutralize land mines, including the use of exothermic reactions aimed at burning the land mines, as opposed to detonating them. During a six-week period ending in June 1998, trials were conducted with two thermite-based mine/unexploded ordnance (UXO) destruction systems, one marketed by CIL/Evan and one by Dew Engineering. All mines tested were partially or fully exposed. Both thermite systems caused most metallic mines to detonate after variable periods of burning. Thermite was generally more effective against mines with a smaller amount of explosive (anti-personnel (AP) mines) and mines with Bakelite or plastic casing materials. The CIL/Evan product, being a loose powder, was more adaptable to unusual surface contours. The solid DEW unit was less suitable for surfaces that were uneven or not level. Both systems are considered non-explosive and non-flammable by current transport and storage safety regulations. Their unit costs are comparable to military pattern explosives. This study indicates that thermite might be applicable in limited circumstances only—perhaps where the mines are exposed or removed, unfused, and when disposal explosives are unavailable or difficult to obtain.

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Unexploded Ordnance
UXO
Humanitarian demining