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INCENDIARY DEVICES
FOR THE IN-SITU COMBUSTION OF CRUDE OIL SLICKS

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INCENDIARY DEVICES FOR THE IN-SITU COMBUSTION OF CRUDE OIL SLICKS

by

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ABSTRACT

This report summarizes the development of incendiary devices for the in-situ combustion of confined crude oil slicks in a remote environment. Several design parameters characterising a suitable incendiary device for this purpose are discussed, both in qualitative and quantitative terms. Three prototype incendiary devices are described in detail, with particular attention being given to the processing and testing of the pour-castable incendiary compositions employed in these devices. These compositions are based on an ammonium perchlorate oxidizer, a metal powder fuel, and a polymeric binder. A comprehensive testing program of the prototype designs is reported, leading to the selection of the peripheral-burning design as the most promising candidate. This incendiary device, incorporating its own pyrotechnic delay igniter and containing some 1.6 kg of incendiary composition (56% $NH_4C\ell O_4$, 25% $A\ell$, 18% binder, 1% thixotropic agent), provides a 1700°C burn for over two minutes, dissipating a sufficient quantity of heat to bring about a self-sustaining combustion of thin weathered crude oil slicks.

RÉSUMÉ

Ce rapport porte sur le développement des dispositifs incendiaires pour le brûlage sur place de nappes d'huile brute dans les régions éloignées. On discute des principales caractéristiques d'un dispositif incendiaire approprié à cet usage et on décrit en détail trois prototypes de dispositifs incendiaires en accordant une attention particulière à la fabrication, à la mise en oeuvre et à l'évaluation des compositions incendiaires coulables qu'ils contiennent. Celles-ci se composent principalement d'un oxydant, le perchlorate d'ammonium, d'un carburant, une poudre métallique, et d'un liant polymérique. On présente l'évaluation détaillée des divers prototypes qui a permis de choisir le dispositif incendiaire à combustion périphérique comme candidat le plus prometteur. Ce dispositif, qui renferme son propre allumeur pyrotechnique à retardement et 1.6 kg de composition incendiaire (56% $NH_4C\ell O_4$, 25% $A\ell$, 18% de liant, 1% d'un agent thixotropique), produit une flamme de 1700°C d'une durée de 2 min, dégageant ainsi une chaleur suffisante pour provoquer la combustion d'une mince nappe d'huile brute.

TABLE OF CONTENTS

1.0 INTRODUCTION

Hydrocarbon slicks floating on open water, whether resulting from undersea well blowouts or shipping mishaps, can be highly detrimental to the surrounding marine environment. With more and more undersea exploratory and production oil wells being built and a growing volume of shipping traffic that relies on progressively larger tankers, the possibility of such contamination of the environment is greatly increased. This potential danger is further increased by exploratory wells and shipping routes steadily spreading north into perilous, ice-infested waters, where the likelihood of accidental spillage is even higher.

To date, no completely satisfactory method for the cleanup of these slicks has been found. While containment and recovery techniques have a limited application under certain ideal conditions, a large-scale spill on the open seas generally precludes their use. In Arctic locations, the remoteness and hazardous ice conditions would further discourage operators from attempting any cleanup.

The most practical, if not at times the only, solution for disposing of many of these spills is in-situ combustion. While often regarded as a last-resort measure since the resulting smoke and residual sludge themselves pollute the environment, the harmful effects of the spill can be reduced by as much as 90%.

In the North, the remoteness of the location and the dangers presented by the ice further support the decision to use in-situ combustion. In a typical oil spill scenario it is conceivable that a blowout could occur near the end of the drilling season, and the forthcoming freeze-up would force the operator to abandon the site before capping the well. In this case, the blowout would run wild until being capped during the next drilling season. It is hypothesized that in the interim the crude oil would accumulate under the ice and gradually become encapsulated in the ice cover as the latter increased in thickness throughout the course of the winter. During the spring thaw the crude oil would percolate up through brine channels in an essentially unweathered state, forming slicks on literally thousands of melt pools. The overall extent of the contaminated region could measure as much as 50-100 km wide by some 400 km long, which to some extent traces the wandering of the pack ice above the uncapped well during the winter. Owing to the vastness of the affected area, the precarious nature of the ice cover, and the remoteness of the spill site, it would be logistically impossible to move men and equipment onto the ice surface for cleanup operations. The only viable solution would be in-situ combustion, where each slick would have to be ignited by incendiary devices deployed from low-flying aircraft.

The Environmental Emergency Branch of the Environmental Protection Service, Environment Canada, is concerned with the development of effective countermeasure techniques for use in the event of a major oil spill in the North. The Arctic Marine Oilspill Program (AMOP) was initiated in late 1976 to coordinate this development in view of the accelerated growth of oil exploration activity in Arctic offshore waters (Ref. 1). The lack of proven countermeasures to deal with an oil well blowout or any large oil spill in ice-covered and ice-infested waters emphasized the need for this program.

As well as various theoretical studies including blowout behaviour, oil spill distribution, biological effects and sensitivity mapping, AMOP considered feasible methods of carrying out oil spill containment, recovery, dispersement and in-situ combustion. The last method has received considerable attention in view of the logistics involved in combatting an oil spill in the Arctic environment.

Studies commissioned by Environment Canada and other agencies (Refs. 2-4) concluded that in-situ combustion was a very viable alternative for significantly reducing the harmful impact of a major oil spill on the fragile Arctic biota. An effective incendiary device to initiate the combustion was required in view of the scenario involving thousands of contaminated melt pools where each must be lit separately.

In early 1978 Environment Canada approached the Department of National Defence to provide assistance in the development of a suitable incendiary device. Environment Canada recognized that a propellant-type or pyrotechnic-based material would be ideal for igniting the oil slicks and Defence Research Establishment Valcartier (DREV) possessed expertise in working with materials and devices of this nature. An interdepartmental Memorandum of Understanding (Ref. 5) was signed directing DREV to provide technical assistance to AMOP in developing a helicopter-deployable incendiary device capable of igniting oil in melt pools in the Arctic.

This work was performed at DREV between January 1979 and May 1982 under PCN 21B43 Assistance to Department of the Environment - AMOP.

2.0 REQUIREMENTS OF INCENDIARY DEVICE CANDIDATES

The phenomena of ignition and subsequent combustion of hydrocarbon slicks (and other combustible materials in general) have been fairly well investigated both theoretically and experimentally (Refs. 6-9). A detailed analysis of these processes is beyond the scope of this report and hence only some of the more pertinent aspects of incendiary device design will be mentioned.

Crude oil slicks floating on water, regardless of their origin, will under certain conditions burn vigorously when lit. The actual ignition however is often deceptively difficult. The problem is created by the slick thinning out to the point where the heat energy input to initiate combustion is lost to the underlying water (which serves as an infinite heat sink) rather than conserved within the slick to raise its local temperature to the fire point. The problem is further aggravated by the chemical and mechanical degradation of water-in-oil emulsions. This tends to remove or isolate the more volatile components, raising the fire point and making ignition substantially more difficult.

The requirements for a successful incendiary device are thus easily defined in broad terms: it must be capable of generating heat in sufficient quantity, with a correspondingly high heat flux to the slick surface, to raise the temperature of a portion of the slick above the fire point to bring about surface ignition. Furthermore, the area of the preheated surface must be large enough that the combustion of the crude is self-propagating by the time the incendiary device has completed its burn, i.e. when the unsteady burning stage immediately following ignition is over.

In more specific and quantitative terms, however, it is difficult to define the minimum requirements for a successful incendiary device. Theoretically one can attempt to analyse the properties of the crude oil slick in a particular configuration and from this determine the minimum heat flux necessary to be imparted to the slick (Ref. 7). In general, it can be simply stated that combustion will be achieved only if adequate heat is supplied to the slick to raise its temperature to the fire point and vaporize the fuel. This heat must be supplied at a rate faster than that at which heat is lost to the water below and the atmosphere above. The heat flux required is largely dependent on slick thickness, the flash and fire points of the crude, its state of degradation (weathering), and the wind conditions. Other oil slick properties that will affect ignition and combustion are density, heat capacity, thermal conductivity, initial temperature, and the heat of vaporization.

The required heat flux that must be directed onto the slick is quite substantial, which means that the incendiary device should not only be capable of producing this high amount of heat flux but also be efficient in transferring the heat to the slick. Apart from good incendiary device design, this implies that the surface reflectivity of the crude oil slick over the wavelength band of the radiant source must be minimal. Furthermore, the radiant source must dissipate heat for a sufficient length of time so that self-sustaining combustion of the slick can be initiated.

In view of the Arctic oil spill scenario described previously, the remoteness of the possible spill sites and the magnitude of contaminated areas, the incendiary device must be deployable from low-flying aircraft. It should be sufficiently compact that a large number could fit inside an aircraft so that, during a mission, the aircraft would have to return to the base location for lack of fuel rather than lack of incendiary devices.

Operational and logistical factors that form the basis of the design criteria for a successful incendiary device are discussed in detail in Ref. 10. The design specifications for the device require that it:

a) float freely in 10 cm of fresh water;

b) function in both fresh and salt water;

c) heat an area of at least 0.3 m^2 without overly disturbing the surface or self-propelling;

d) generate heat for at least 2 min in sufficient quantity to raise the surface temperature at the boundary of the heated area to at least 100°C at an ambient air and water temperature of 0°C, providing the oil is at least 0.5 cm thick;

e) provide an ignition source within the oil vapour zone;

f) permit adequate air supply to the combustion zone;

g) be capable of storage for at least 5 years at a temperature range of -50°C to +50°C;

h) have at least a 95% probability of functioning properly when dropped at an airspeed of 15 knots from an altitude of 15 m into water that may only be 10 cm deep over a solid ice surface. Preferably, the device should have at least the same probability of functioning when released at a speed of 30 knots and an altitude of 15 m into 10 cm of water over ice, or if released into deeper water (at least 1 m) from an altitude of 60 m and an airspeed of 60 knots;

i) delay commencement of heat generation until at least 20 s after impact to allow surface conditions to recover from rotor downwash effects or the disturbance created by the landing of the device;

j) be safe from premature activation or other conditions associated with carriage and release from the type of aircraft involved;

k) be operable by typical aircraft crewmen who have received no more than a simple briefing beforehand;

l) have a unit weight of not more than 2 kg; 225 units and the associated airworthy stowage arrangements should not occupy a space exceeding 0.75 m wide, 1 m long and 1.3 m high; and

m) require not more than 10 s to remove an igniter from its storage, prepare it for dropping, aim, fire and release it manually towards its target.

3.0 PRELIMINARY DESIGN CONSIDERATIONS

Based on previous background studies, there were two groups of potentially viable materials to fuel the incendiary device:

a) a propellant-type material containing a metal fuel that provides a high heat of combustion; and

b) mixtures of combustible carbonaceous fluids that would spread over the slick while burning.

The latter group, composed mainly of inflammable hydrocarbon oils, is quite efficient in operation but suffers from the drawback of possessing a relatively low energy density. For applications in the Far North, a compact incendiary device capable of a large heat output is of paramount importance.

The former group capitalizes on metal fuels, such as magnesium and aluminum, having high heats of combustion and reasonably low melting points. These fuels are incorporated into a solid rocket-motor-type composition that provides for their ignition and supplies a source of oxygen for their continued combustion. The exact formulation is adjusted to obtain a burning rate lower than that of a propellant, while still maintaining an adequate heat flux, to ensure ignition of the crude oil slick.

In accordance with the Memorandum of Understanding, development work at DREV concentrated only on the former group; namely, development of an incendiary device incorporating composite (rubber-based) propellants and pyrotechnics.

A second factor requiring careful consideration was the method of initiating the incendiary device. At the outset there were four classes of starters worthy of consideration:

1) chemical: reaction upon exposure to water (sodium, potassium) or exposure to salt water (magnesium alloyed with iron, copper or nickel). Reaction upon exposure to air (pyrophoric powders such as finely divided zirconium). Reaction between chemicals following priming (potassium permanganate impregnated with an ethylene glycol solution).

2) electrical: system to function off a storage battery or a water-activated battery, or alternatively be initiated by radio transmitter.

3) mechanical: this could be breaking a seal to promote a chemical reaction, an impact switch in an electrical circuit, or a mechanically fired cartridge. Initiating force to be provided either by crewman in the aircraft or through the landing impact of the incendiary device following air deployment.

4) external impetus: provision of an external shock, introduction of priming agent, ignition of a fuse wire, etc., performed in the helicopter.

In consideration of storage life requirements, cost, reliability, and ease of deployment, a mechanical igniter forming an integral part of the incendiary device was chosen. The igniter consists of a spring-loaded striker which is activated by a crewman, causing it to impact and initiate a small primer cap. This ignites a slow-burning delay column which, after a given delay time, ignites the main incendiary filling via an ignition transfer composition.

A final important factor was the mechanical layout of the device. While being governed in part by the incendiary formulation and the type of igniter used, the design was to provide adequate floatation for the device to permit its proper functioning, while at the same time be sufficiently robust in structure to withstand the landing impact following air deployment.

Three prototype designs for the incendiary device are described in Chapter 4.0. After testing, the first design was discarded for reasons that shall be discussed. The second and third designs showed themselves to be potential candidates for filling the role of the incendiary device, and their development was carried through to the preproduction stage.

4.0 PROTOTYPE DESIGNS

A composite composition consisting of a metal fuel, an oxidizer, and a rubber binder is particularly well-suited for this application. Its main advantage is its high heat of reaction. Depending on the exact formulation, observed flame temperatures in excess of 2000°C are possible and the heat flux per unit mass is about twice the lower heat value for simple hydrocarbon fuels, or some four times the heating value of these fuels under actual burn conditions (i.e. oxygen excess). Since the composite composition contains its own supply of oxygen, the reaction will at all times be near stoichiometric and will not be readily susceptible to extinction by water, ice floes, or wind.

4.1 Cigarette-Burner Cylinder

As an initial prototype, a cylinder consisting of incendiary composition cast in a cardboard tube was adopted for testing. The cylinder had dimensions of 7 cm in diameter by 18 cm in length, and was intended to float more or less horizontally on the slick surface. The flame and heat were to emanate from one end over the slick surface, without additional mechanical support or a floatation collar.

The incendiary composition was cast directly in cardboard tube moulds, to which it bonded upon curing. This cardboard tube served the additional purpose of preventing the flame front from spreading in an uncontrolled manner up the side of the cylinder, and hence enabled the cylinder to burn uniformly from one end to the other in cigarette fashion.

A filler, not normally part of a propellant composition, was incorporated into the incendiary formulation to (a) regulate the burning rate of the composition and (b) reduce the density of the composition so that it would float on water. The filler was in the form of minute hollow spheres commonly known as microballoons, having a true density ranging from 0.15 to 0.35 g/cm^3 depending on type (sodium borosilicate glass, ceramic, or phenolic) and average diameters ranging from 50 to 100 µm. The concentration of filler was adjusted to give the incendiary device an overall density of about 0.9 g/cm^3 while at the same time maintaining desirable burning characteristics.

Selected compositions tested for this prototype appear in Table I. Other compositions were tested and judged unsuitable owing to poor processing characteristics or poor performance. These included gas generator compositions, which were typically 57% NH_4NO_3 (with 1% ALON), 19% guanidine nitrate and 24% binder. At high pressures these are slow burning when compared to propellants; however, during testing at ambient pressures the combustion failed to propagate and hence the compositions were not usable.

The formulations reported in Table I were cast in cardboard tube moulds. Others were cast in tubes consisting of neoprene or rocket motor insulating materials such as RF/B (roll-formed type B) or CF/P (carbon-filled polymer). These failed to produce desirable burning performances and were hence discarded.

TABLE I

Prototype compositions for cigarette-burner cylinder

Batch Designation	NH_4ClO_4 Oxidizer(1) (%)	Binder(2) (%)	Filler(3) (%)	Burning Rate (mm/s)
CRV7	88	12	-	1.26
AM-1	80	20	-	0.98
AM-5	75	20	5 PMB	1.20
AM-7	70	30	-	0.60
AM-2	70	20	10 GMB	1.06
AM-8	65	30	5 GMB	0.75
AM-3	65	20	15 GMB	1.20
AM-9	60	30	10 GMB	0.77
AM-12	60	30	10 PMB	0.70
AM-10	55	30	15 GMB	0.72
AM-16	50	30	10 PMB, 10 KCℓ	0.64
AM-17	40	30	10 PMB, 20 KCℓ	0.53

1 - Blend of 2/3/5 parts by weight of 400 μm/200 μm/17 μm.
2 - Binder: typically 60% R-45HT prepolymer (Arco Chemical Co.),
15% DDI-1410 curing agent (General Mills),
25% Emolein 2911 plasticizer (Emery Industries).
3 - PMB: phenolic microballoon.
GMB: glass microballoon.

The most promising compositions (Table II) were further tested at Energetex Engineering, Waterloo, Ontario for their ability to ignite thin slicks of aged crude oil. The cylinders incorporated a recess at one end to house the igniter, which was a high-density polystyrene sphere containing potassium permanganate powder that was activated by the injection of a 50% ethylene glycol solution. The overall density of the device was slightly less than that of water to enable the device to float on the pool surface and function as a flame thrower over the slick.

TABLE II

Trials of candidate compositions at Energetex

Batch Designation		Oxidizer NH_4ClO_4 (% by wt.)	Binder (% by wt.)	Filler (% by wt.)	Overall Density (g/cm^3)	Burning Rate (mm/s)
OP	AM					
02	32	55	30	15 GMB	.98	0.8
03	16	50	30	10 PMB 10 KCl	.81	0.75
04	12	60	30	10 PMB	.93	1.3
05	26	55	30	15 PMB	.80	1.1
06	34	50	30	20 CMB	1.15	0.6

Notes:
PMB - phenolic microballoon
GMB - glass microballoon
CMB - ceramic microballoon

Results of these tests appear in Table II. In general this design was a rather poor performer for several reasons. The low aspect of the device in the water caused the combustion front to be thermally quenched. To alleviate this difficulty the device was placed on top of an improvised floatation pad, allowing it to burn properly. However, the force of the combustion gases tended to push the oil away from the vicinity of the incendiary device and the heat was wasted on the open water.

The igniter also needed modifying. Upon being ignited and thrown into the test pool, water tended to leak into the sphere and further dilute the ethylene glycol to the extent that no reaction would occur. Restriction of the hole after introduction of the glycol would only cause the sphere to blow apart before ignition of the incendiary filling could take place.

When functioning in its most desirable orientation, this prototype incendiary device was able to ignite crude oil slicks of 4 mm in thickness. However in view of the performance problems encountered, it was apparent that the incendiary device required an extensive redesign which would include an alternate method of effecting the delayed ignition.

As an immediate solution to the problem the incendiary composition was housed in a polystyrene mould and a new type of delay igniter, to be described later, was inserted (Fig. 1). The polystyrene housing provided improved floatation of the device by eliminating direct contact between the incendiary composition and the water, while at the same time giving the device a proper orientation so that the radiant heat flux would emanate directly onto the slick surface. The incendiary composition was modified to contain a smaller proportion of ammonium perchlorate; less gas would therefore be generated and the problem of the flame pushing the slick away from the vicinity of the device would be minimized. As a more vigorous combustion was

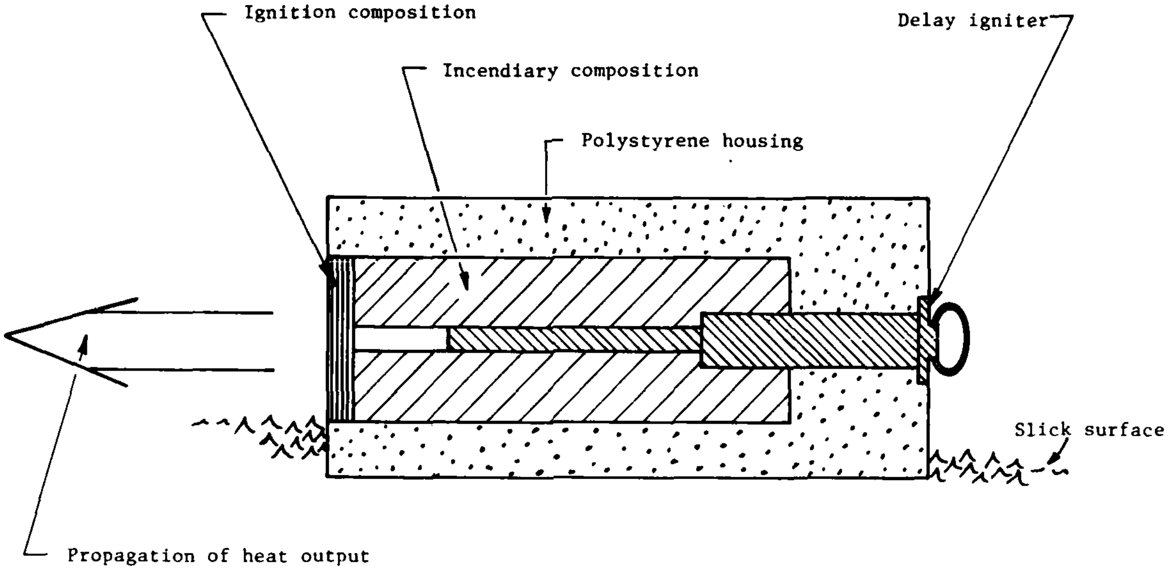


FIGURE 1 - Cigarette-burner cylinder

preferable even at the expense of a higher density composition, the use of low-density fillers such as microspheres or granular cork was discontinued. In their place, an appreciable amount of fuel (aluminum or magnesium) was added to provide for a hot vigorous combustion. The elimination of fillers also permitted a reduction of the proportion of binder.

In practice, the design was a poor performer as it suffered from several distinct drawbacks:

1) The device burnt essentially as a flame thrower, with the flame physically pushing the crude oil out of reach. Furthermore, the expulsion of gases tended to propel the device and so no localized preheating could be achieved.

2) It was nearly impossible to maintain the proper attitude of the device at all times during burn because of its continuously receding centre of gravity. As a result much of the heat was lost either to the open water or the atmosphere.

3) The flame would invariably burn away the exposed portion of the polystyrene mould. The incendiary device would thereafter roll over in the water and float with a lower aspect, causing the combustion to be thermally quenched as a result of direct contact with the water.

4.2 Canister-Type Incendiary Device

A radical design change was made to eliminate the difficulties encountered with the cigarette-burner prototype. The resulting configuration is illustrated in Fig. 2. Operation of this prototype is described to some extent below and other details can be found in Refs. 11 and 12. The exact nature, casting, and curing of the incendiary composition as well as field testing of the incendiary device are given in detail later in this report.

The incendiary device consists principally of a pyrotechnic delay igniter, the incendiary composition and a heat-reflecting dome. The first two are encased in a thin metal jacket with the remainder of the space filled by a polypropylene honeycomb insert to provide adequate buoyancy and absorb the shock at impact following air deployment. The device weighs approximately 1.8 kg, 1.1 kg of which is incendiary composition.

At the moment of deployment from the aircraft, the safety pin is pulled and the spring-loaded striker is armed and released by pulling on the firing clip. The striker initiates a small 9-mm primer cap which in turn activates burning of the delay column. This column burns

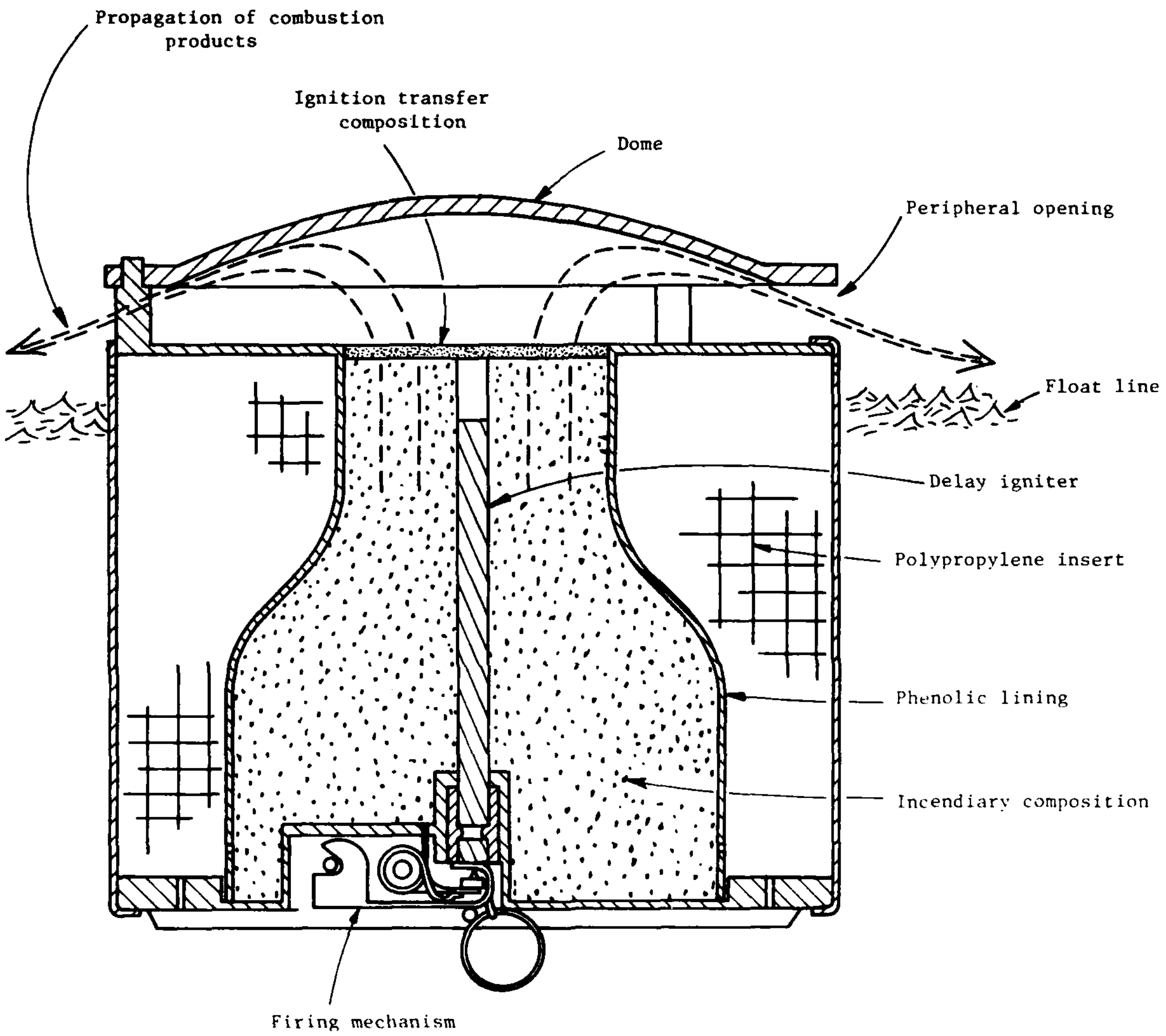


FIGURE 2 - Canister-type incendiary device

at a rate of about 5 mm/s; after approximately 20 s, the burn reaches the end of the delay column and ignites the transfer/igniter powder, the ignition composition, and finally the incendiary composition.

The delay column of the pyrotechnic delay igniter is 'gasless', there is little resultant pressure buildup during the course of its burn and hence it is suitable for a confined location. Accidental firing of the igniter is eliminated by the presence of the safety pin. Furthermore, because the striker is unarmed until the moment of deployment (the spring has no torque applied) and because it is physically isolated from the primer cap by the firing clip, the possibility of activation of the delay igniter by vibration is remote. The safety features and long delay inherent in this igniter make it suitable for deployment from aircraft; the simple design, ease of activation, and reliability of operation make it appropriate for this application.

The incendiary composition burns at its upper exposed surface and as the burning continues, this surface recedes at a rate of approximately 1.0 mm/s to provide a nominal 2-min heat output. In this arrangement the composition burns in cigarette fashion. The intense flame and hot gases produced by the combustion are directed vertically upwards to impinge upon the heat-reflecting dome, which redirects them radially outwards through the peripheral vent and onto the slick surface. The size of this peripheral opening (i.e. the standoff of the dome) was adjusted to provide maximum heat flux onto the slick surface.

The space between the main body of the incendiary device and the dome is initially filled with polystyrene foam. This receives and absorbs the impact shock in the event that the device lands upside down, and helps to quickly right the device prior to burn. The foam is rapidly burned off in the first few seconds following ignition of the incendiary composition. Furthermore, this foam extends beyond the dome to form a square shape, thus preventing the device from rolling in the aircraft should it slip from the crewman's hands during deployment.

The heat-reflecting dome is of paramount importance to the efficient operation of the device. Constructed of a glass-fibre-filled phenolic (as is the top disc and the insulating liner), the dome is capable of withstanding the 2300°C temperature throughout the course of the burn. It deflects the flame and gases and reradiates the heat onto the slick surface, heating the latter by both convection and radiation. The glass fibres used in the material are interwoven to structurally reinforce the dome, permitting it to withstand both the physical shock of impact following air deployment and the thermal shock due to rapid heating from ambient temperature to 2300°C.

The insulating liner between the incendiary composition and polypropylene insert plays a double role: it funnels the flame and hot gases upward towards the dome, and it provides a mould in which the incendiary composition is directly cast. A coating of aluminum paint is applied to the interior surface of the liner to improve the adhesion of the incendiary composition, as the bond might otherwise be inadequate. This is a vital requirement for the composition to burn in a cigarette-like fashion.

The overall size of the outer jacket was chosen to give the incendiary device a low aspect in the water to make it stable and to position the heat-reflecting dome close to the slick surface. As the incendiary composition is consumed, the device tends to rise in the water because of its decreasing mass. To offset this, water is allowed to leak in through the bottom portholes to compensate for mass lost through combustion, filling the open cores of the polypropylene honeycomb. In this way the incendiary device maintains its low stable aspect in the water until completion of burn. At the time of burnout, scuttling holes open, water enters the space formerly occupied by the incendiary composition and the remains of the device sink.

4.3 Peripheral-Burning Incendiary Device

An alternate design was developed and tested at the same time as the canister-type device discussed previously. The device is illustrated in Fig. 3 and is described in some detail below as well as in Refs. 12 and 13. The device is of a greatly simplified design compared with the canister type, consisting essentially of a slab of incendiary composition sandwiched between two wood laminate discs and polystyrene foam floatation pads.

This prototype has a total weight of 2.0 kg, about 1.6 kg of which is incendiary composition. The overall dimensions of the device are approximately 25 cm in diameter by 11.5 cm in thickness. The incendiary composition itself is about 22 cm in diameter by 2.5 cm in thickness.

The floatation pads serve three purposes: they protect the device by absorbing the shock at impact following air deployment, they provide adequate buoyancy on the slick surface, and one of the pads houses the pyrotechnic delay igniter.

Ignition of the device is accomplished in a manner similar to that described for the canister-type device. Upon removal of a safety pin, the firing clip is pulled back until it extends beyond the housing of the igniter. This allows the spring-loaded striker to escape from the firing clip, enabling it to impact and fire the primer cap. The firing of the primer cap initiates the gasless delay column, which upon completion of its burn ignites the incendiary composition via the ignition transfer powder and the ignition composition.

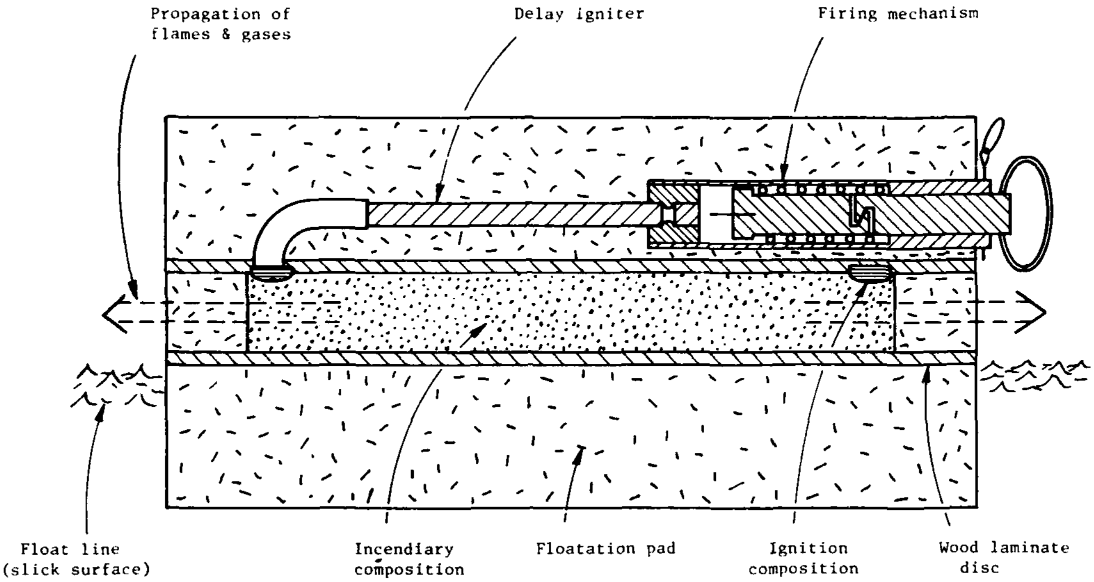


FIGURE 3 - Peripheral-burning incendiary device

The ignition composition surrounds the main incendiary composition onto which it is vulcanized in a groove. Alternatively, as illustrated in Fig. 3 and discussed in Section 5.2, the ignition composition can be pressed into a groove located in one of the wood laminate discs. Being a fast-burning formulation, it serves to ignite the entire peripheral surface within a few seconds to provide a symmetrical burn about the circumference.

The wood laminate discs direct the flame and gases radially outward to skim over the local slick surface. These discs prevent the polystyrene foam from melting or burning, and hence the device from sinking or tilting. They also augment the rigidity of the device, providing a greater resistance to impact.

The major advantage of this device over the previous one is its simpler design, which would lower production costs. In addition, the testing program described in a later chapter revealed that the shallower draught requirement (4 cm vs. 10 cm for the canister type) was a definite advantage.

5.0 FORMULATION AND PROCESSING OF COMPOSITIONS

5.1 Incendiary Composition Formulations

The incendiary compositions employed in the canister-type and peripheral-burning incendiary devices bear some resemblance to the solid-composite propellant of a rocket motor insofar as processing and formulation of major ingredients are concerned. For this application, however, the proportions of ingredients have been altered, and others added, to yield the desirable properties of a steady, controlled slow combustion (0.7 to 1.2 mm/s) while at the same time providing a high flame temperature and a large radiant heat flux. General processing characteristics such as the behavior of the composition in mixing, casting and curing, its mechanical properties, and a minimum batch-to-batch variation during production are other important factors that govern the final choice of formulation.

Combustion performance characteristics of selected formulations of the incendiary composition are presented in Tables III and IV as well as in Figs. 4 and 5. The formulations containing magnesium powder as the fuel were found to be suitable for use in the canister-type incendiary device. Although the burning rates were relatively high, the incendiary filling was sufficiently long and the combustion surface relatively small that an adequate burn time approaching 2 min could be achieved. Magnesium-fuelled compositions were observed to have high flame temperatures and give off only a few sparks in a dispersed fashion. The heat-reflecting dome of the device was able to withstand these high temperatures and distribute the heat flux over a large area of the local slick surface.

Among the magnesium-fuelled compositions, formulation AM-62, with a high magnesium content, provided one of the better performances (flame temperature: 2250°C, burning rate: 1.02 mm/s). To reduce the end-of-mix (EOM) viscosity from 8.8 kP to a lower value in the range of 3 kP and to obtain an easily processed mix, the binder content was increased slightly and the final composition that was loaded into the canister-type incendiary devices was 19.5% binder, 50.5% ammonium perchlorate and 30% magnesium. This composition also provided a burning rate of 1.02 mm/s but its flame temperature was reduced to 2000°C. This was not, however, considered to be a disadvantage as the heat output was still very high and the dome was able to sustain more easily the reduced flame temperature.

The peripheral-burning incendiary device, on the other hand, had a larger burning surface and so required a slower burning composition to attain an adequate burn time. Here, the compositions containing aluminum as the fuel were used. Despite the lower flame temperatures, they provided an intense source of heat owing to a concentrated stream of sparks emanating from the large burning surface. (These compositions were found to be unsuitable for use in the canister-type device as the products of combustion tended to erode the heat-reflecting dome too quickly.)

TABLE III

Performance characteristics of selected magnesium-fuelled compositions

Identification		Composition (% wt.)			Viscosity	Hardness	Flame	Burning
Mix	Formulation	Binder	NH_4ClO_4	Mg(3)	EOM, kP	Shore"A"/ Days at 60°C	Temperature (°C (4))	Rate (mm/s)
16	61	18	67	15	2.5	46/6	2200	1.0
17	69	18	57	25	4.1	43/5	2350	1.06
22	60	20	65	15	1.0	35/4	2150	0.98
23	61	18	62	20	2.7	38/4	2350	1.02
24	62	18	52	30	8.8	40/4	2250	1.02
31	69	18	57	25	4.5	40/4	----	1.24
33	61	18	62	20	2.3	40/4	2350	1.17
40	62	18	52	30	8.5	----	2150	1.13
41	78	20	50	30	2.8	----	2000	1.02
42(1)	78	20	50	30	1.6	----	----	----
43(1)	79	19.5	50.5	30	3.0	----	----	----
48(2)	79	19.5	50.5	30	2.4	50/4	----	----
49(2)	79	19.5	50.5	30	2.5	46/3	----	----

1: Large scale batches (25 kg in 10-CV mixer); canister and peripheral-burning devices for development and drop tests at Energetex and Lac Laurier.

2: Large scale batches, canister-type devices for Arctic field trials.

3: Magnesium powder: spherical grade, 200/325 mesh, Metal & Alloys Co.

4: Flame temperatures measured using a "Capintec Thermoscope" two-colour optical pyrometer.

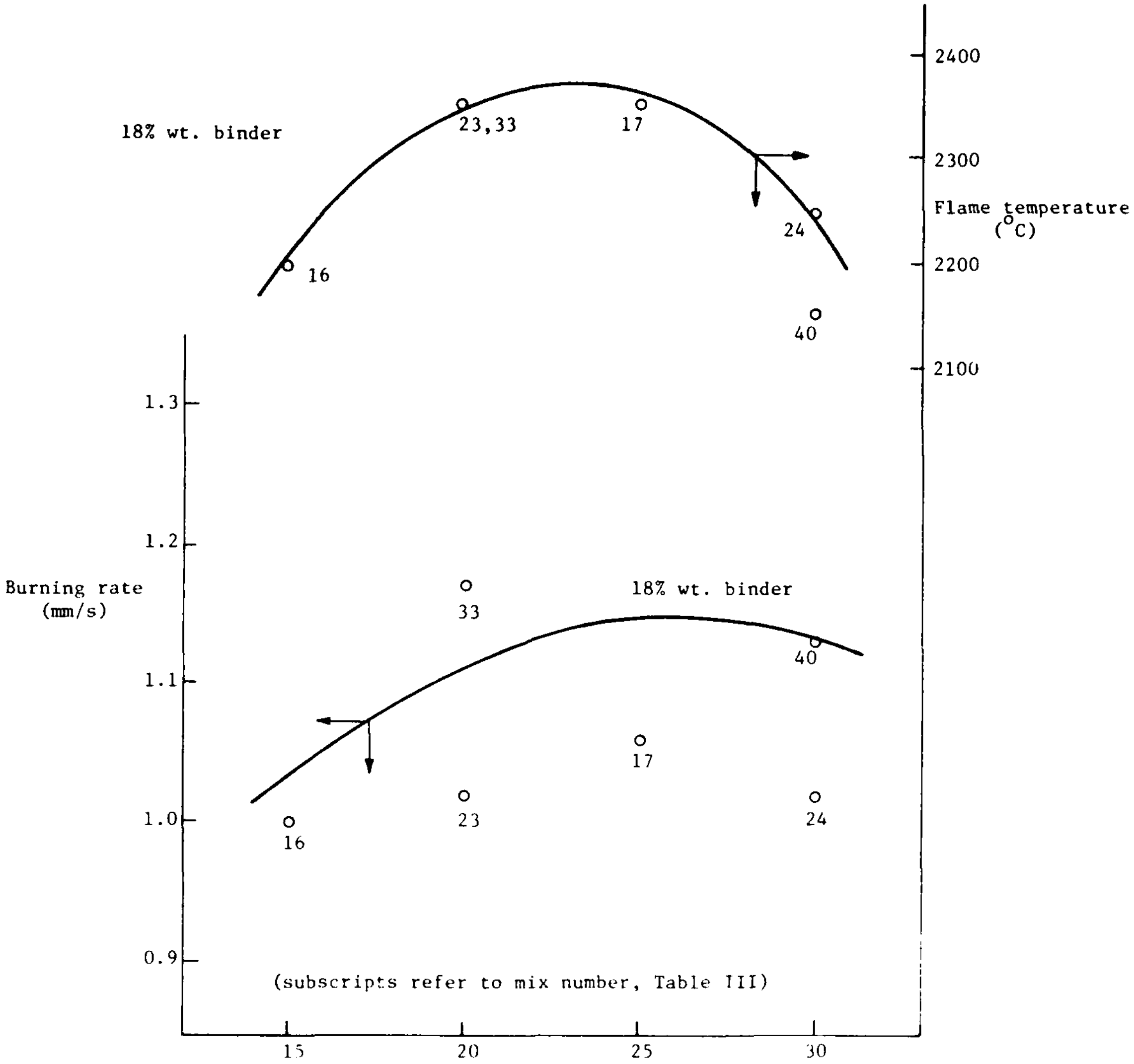


FIGURE 4 - Burning rates and flame temperatures of magnesium-fuelled formulations

TABLE IV

Performance characteristics of selected aluminum-fuelled compositions

Identification		Composition (% wt.)				Viscosity	Hardness	Flame	Burning
Mix	Formulation	Binder	NH_4ClO_4 (1)	Al(2)	Thixcin(3)	EOM, kP	Shore"A"/ Days at 60°C	Temperature (°C(6))	Rate (mm/s)
11	64	15	70	15	--	3.4	39/4	2090	0.91
13	66	15	65	20	--	2.0	36/3	2200	0.93
14	68	15	60	25	--	1.1	38/3	2150	0.93
15	70	15	55	30	--	0.9	46/6	2250	0.92
19	57	20	65	15	--	0.6	35/6	1500	0.77
20	58	20	60	20	--	0.5	33/6	1450	0.72
21	59	20	50	30	--	0.3	34/6	1420	0.60
30	70	15	55	30	--	0.8	40/4	----	0.93
32	58	20	60	20	--	0.3	30/4	1500	0.79
36	74	20	50	29	1	3.0	30/4	1600	0.69
39	77	18	56	25	1	3.1	30/3	1680	0.74
46(4)	77	18	56	25	1	4.4	27/3	----	----
47(4)	77	18	56	25	1	3.7	35/3	----	----
60	84	18.25	56	25(5)	0.75	2.4	30/4	----	----

1 - Ammonium perchlorate: blend of 2/3 parts of 400 μm/200 μm (Kerr-McGee Chem. Corp.).
2 - Aluminum powder: H-15, 20-μm mean size (Alcan Ingot and Powders).
3 - Thixcin-E: fine silica, thickening agent (Baker Castor Oil Co.).
4 - Large-scale batches (25 kg in 10-CV mixer): production of prototypes (peripheral-burning devices) for Arctic field trials.
5 - Aluminum powder: MDX-75 (Alcan Ingot and Powders).
6 - Flame temperatures measured using a "Capintec Thermoscope" two-colour optical pyrometer.

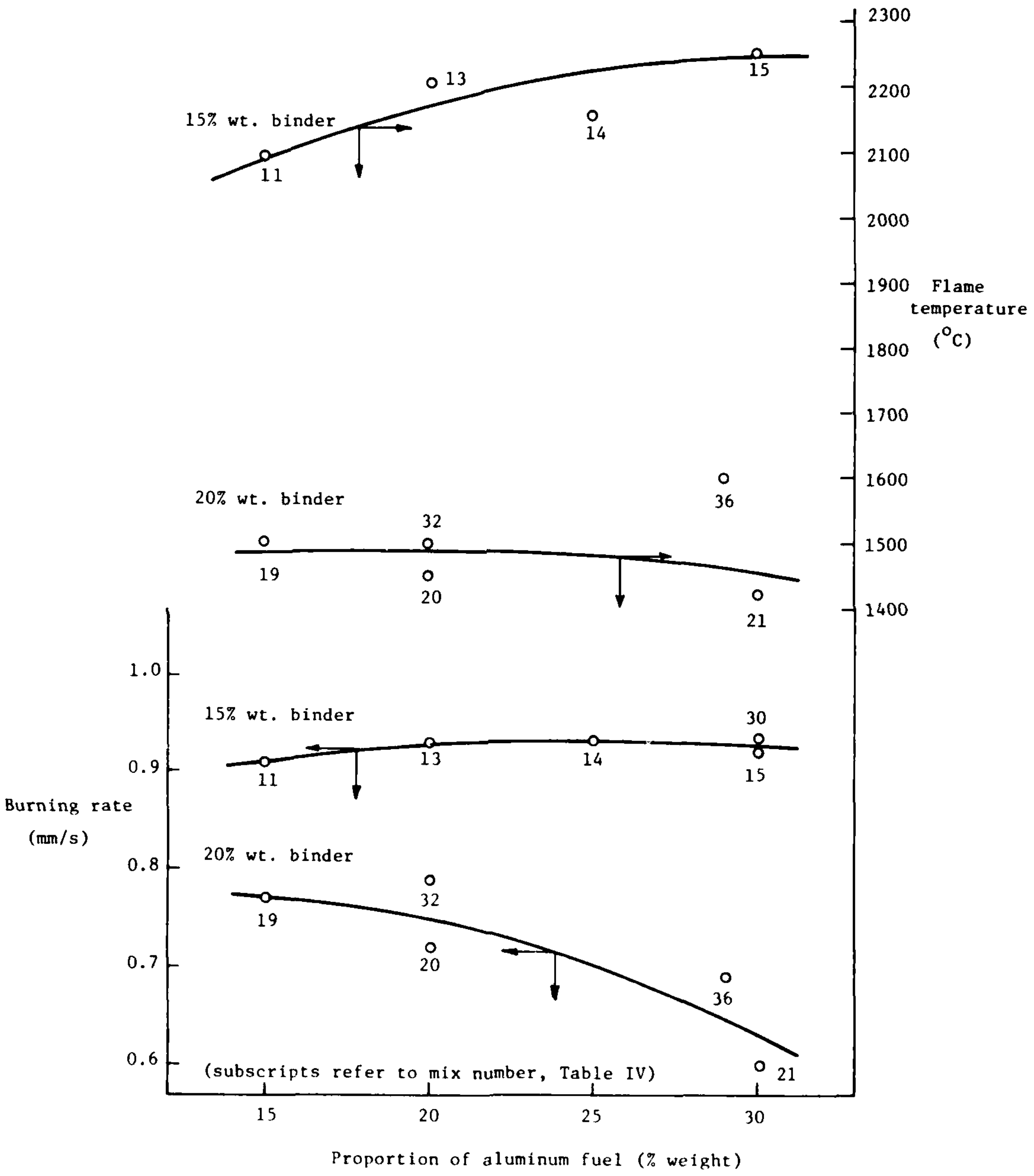


FIGURE 5 - Burning rates and flame temperatures of aluminum-fuelled formulations

The selected composition for the peripheral-burning device contains 18% binder, 56% ammonium perchlorate oxidizer, 25% aluminum powder fuel and 1% thixotropic agent. This formulation (AM-77) provided a burning rate of 0.74 mm/s and a measured flame temperature of 1680°C.

The thixotropic agent, Thixcin-E (Baker Castor Oil Co.), is a finely ground silica powder required to increase the mix viscosity and prevent any sedimentation of ingredients at the curing stage. The 1% level was chosen to yield an EOM viscosity of 3 kP for a formulation containing H-15 aluminum powder (Alcan Ingot and Powders); however, substituting MDX-75 (also marketed by Alcan) for this grade increased the viscosity to 4-5 kP. This is a frequent situation and for this reason a composition with 0.75% Thixcin (and 18.25% binder) was also prepared and showed good performance. Consequently, the Thixcin content can be varied between 0.75% and 1.0% (and the binder accordingly) to maintain the viscosity at 2-3 kP. In this manner the compositions are easily processed by standard propellant industry equipment or even by less specialized equipment.

The binder was the same for all formulations and was based on a hydroxyl-terminated polybutadiene prepolymer (R-45HT manufactured by Arco Chemical Co.). It was cured with a commercial dimeryl diisocyanate curing agent (General Mills DDI-1410) in an NCO/OH ratio of 1/1, and plasticized with an ester such as isodecyl pelargonate (IDP). The formulation of the binder was 59.3% R-45HT prepolymer (including 1% weight of di-tert-butylhydroquinone (DTBHQ) antioxidant), 15.7% DDI-1410, and 25% IDP.

5.2 Incendiary Composition Processing

The incendiary compositions were prepared in Atlantic Research Corp. helicone-vertical mixers; the 8-CV mixer (loaded with batches of 4 to 6 kg) was used for the development of the compositions while the

10-CV mixer was used to process 25 and 35 kg batches for prototype preparation. The capacity of the 8-CV mixer is 9 L while the 10-CV can handle 45 L.

A standard mixing procedure was adhered to during the entire program. The liquid ingredients (the polymer, including the antioxidant and the plasticizer) were first poured into the mixer, followed by the fuel (magnesium or aluminum), and the contents mixed for 10 min at atmospheric pressure with the jacket temperature maintained at 60°C. For cases where a thixotropic agent was used, it was loaded at the same time as the fuel. The ammonium perchlorate and the curing agent were then added separately, with mixing for 5 min after each addition. A vacuum (~5 mm Hg, absolute pressure) was applied and mixing continued for 50 min at 20 RPM, with the mix temperature being maintained at 60°C.

The compositions were next cast directly in their moulds under atmospheric pressure. For larger batches processed in the 10-CV mixer, a transfer pot was used; the mix was cast in the transfer pot that was installed on a press and the composition extruded into the moulds. Curing of the cast composition was then carried out at 60°C. Depending on the formulations, complete curing was achieved in 3-6 days.

In the case of the canister-type device, the compositions were cast directly in the conical phenolic tubes that were coated with an aluminum paint to improve bonding. A Teflon mandrel was inserted to provide the cavity for the firing mechanism and delay column and it was removed upon complete curing of the composition.

Three different methods were used for moulding and assembling the peripheral-burning device. In the first method, the compositions were cast in large 21-cm-diameter by 15-cm-high cylinders that were machined upon complete curing into 2.5-cm-thick by 21-cm-diameter discs as shown in Fig. 6. The ignition composition was then pressed into the

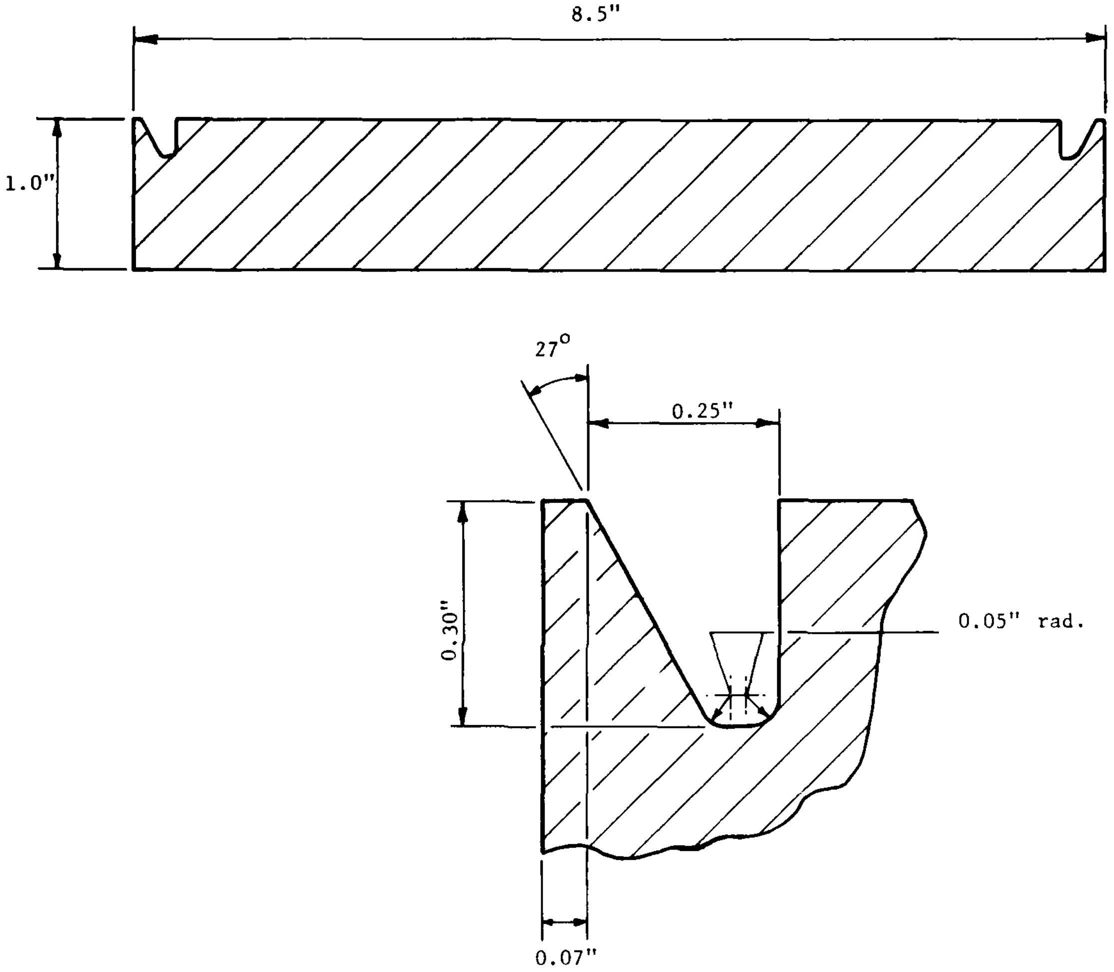
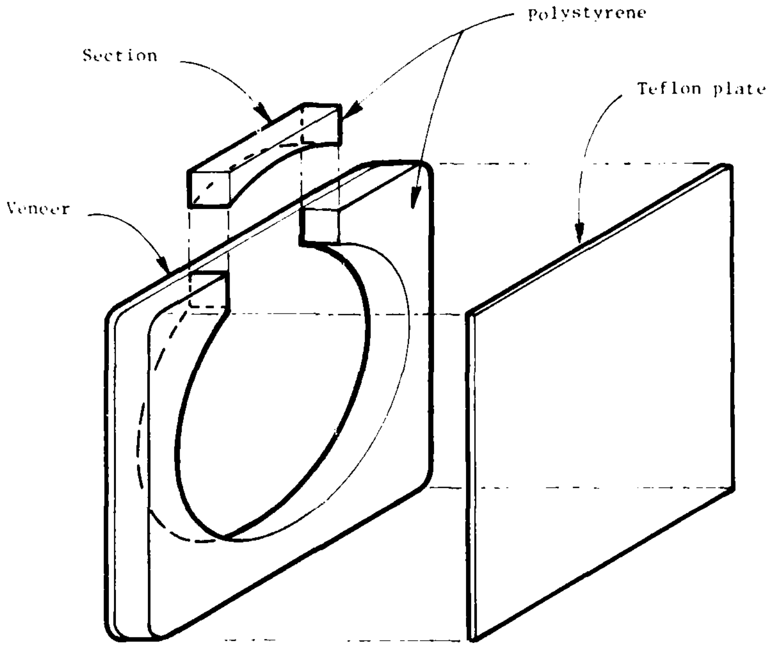
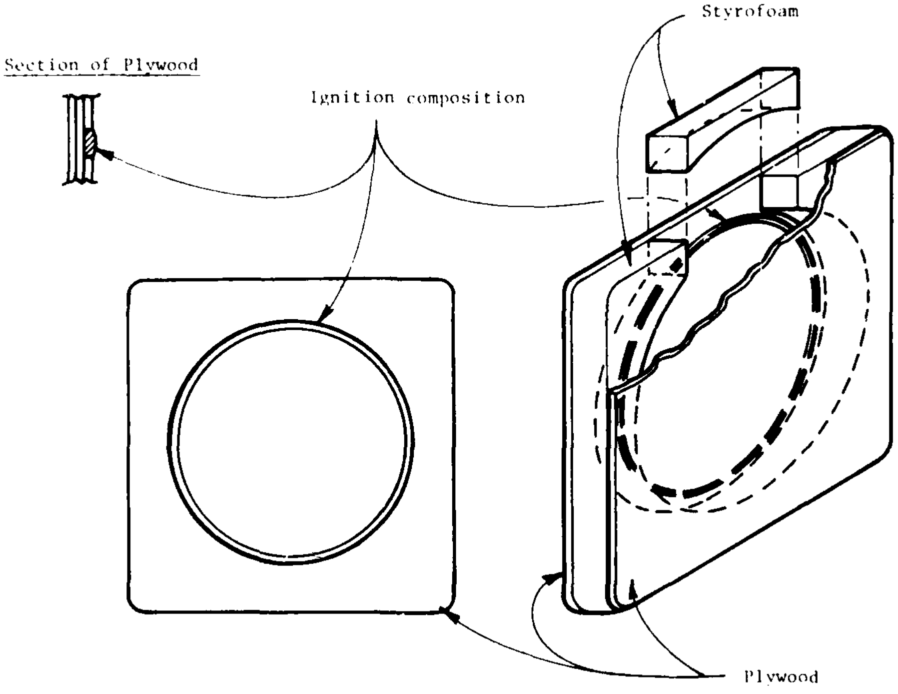


FIGURE 6 - Machined disc of incendiary composition for peripheral-burning device



Mould-A (with Teflon plate)



Mould-B (with Ignition Comp in Plywood)

FIGURE 7 - Moulds for peripheral-burning devices

peripheral groove, after which final assembly of the device took place (Fig. 3). The incendiary slab, plywood discs and polystyrene pads were held together with an alumina-filled polymer binder AF/P (60/20/20 parts by weight of R-45HT prepolymer/DDI-1410 diisocyanate curing agent/alumina hydrate. Ferric acetylacetonate catalyst (0.1%) dissolved in a minimum amount of dichloromethane was used to promote curing). The firing mechanism was affixed inside one of the polystyrene pads with an adequate commercial glue.

A second method consisted in moulding individual discs in a multiple-compartment mould. Each compartment (mould A of Fig. 7) was made of a Teflon plate, a polystyrene ring and a nonperforated plywood disc. A section of the polystyrene ring had been removed to provide an opening. After complete curing of the composition, the moulds were disassembled and the Teflon plate removed. The excess of composition in the opening was cleared away, the groove was made with a hand tool (Fig. 8) and the section replaced. The second plywood disc and remaining components were then assembled in a manner identical to that described above.

The third method was similar to the second except that the groove receiving the ignition composition was located in the perforated plywood disc and the ignition composition was first pressed into this groove and cured. The moulds were then made exclusively with the device component parts, notably the two plywood discs (one already containing the ignition composition) and the polystyrene ring (mould B of Fig. 7). The composition was cast and cured and the polystyrene section replaced. In this case there was no machining of the composition except removal of any excess in the opening. Only the polystyrene section needed an additional adhesive as the incendiary composition bonded all the other parts. Adhesive was also required to join the floatation pads and the firing mechanism.

FIGURE 8 - Hand tool for ignition composition groove

Figure 7 shows devices with an outside square shape. This modification (from round to square) was made to increase air deployment accuracy by preventing rolling of the device upon impact on a hard surface. Another improvement consisted of eight holes in the polystyrene ring (1.8 cm in diameter, 2 per side) to allow for a more efficient ignition sequence.

5.3 Mechanical Properties

Initial mechanical properties for compositions containing 18% to 20% binder exhibited a minimum tensile strength (σ_{min}) of 300 kPa and at least 10% maximum elongation (ε_{max}). Typical results are reported in Table V.

TABLE V

Mechanical properties for Composition AM-85

Aging (days at 60°C)	min (kPa)	ε_{max} (%)	Hardness (Shore A)
0	350	16	31
56	390	14	33

5.4 Safety Tests

A sample of incendiary composition AM-85 (OP-61) was tested by the Canadian Explosives Research Laboratory of Energy, Mines and Resources Canada. The results of these tests are reported in the Explosive Safety Test Certificate No. 40 (CIE #5037). The classification of the composition is as follows:

Explosives Act - Class 1, Division 2; United Nations Code 1.3G;
Transport - Class B;
Safety Distance - Category Y.

5.5 Ignition Composition

The peripheral-burning incendiary device takes its name from the uniform progression of the combustion front about the entire circumferential surface. The required rapid ignition of the periphery is

TABLE VI

Ignition compositions

Formulation No.	Binder (parts by weight)			Solids (parts by weight)		Final Composition (% weight)		Burn Rate (cm/s)
	RHT (1)	Epoxy (2)	Solvent (3)	F-ND (4)	F/FFF (5)	Binder	Solids	
1	-	10	10	40	-	20	80	18.3
2	-	10	20	60	-	14	86	--
3	-	10	40	100	-	9	91	--
4	-	10	5	30	-	24.8	75.2	28.7
5	10	-	5	30	-	24.8	75.2	5.0
6	10	-	10	40	-	20	80	6.8
7	10	-	20	60	-	14	86	14.5
8	10	-	40	100	-	9	91	--
9	10	-	5	-	30	24.8	75.2	2.5
10	10	-	10	-	40	20	80	21.6
11	10	-	20	-	60	14	86	20.8

1- RHT: 78% wt. R-45HT/22% wt. DDI-1410.

2- Epoxy: 85% wt. Epon 815/15% wt. Hysol 3543.

3- Solvent: ethyl alcohol.

4- F-ND: boron-potassium nitrate ignition grains, type K granules (Atlantic Research Corp.).

5- F/FFF: black powder (1 part F grade/2 parts FFF grade).

accomplished by a fast-burning powder that surrounds the main incendiary composition and ignites it within 2.5 s.

Various compositions of the ignition powder (Table VI) were studied, including black powder or boron-potassium nitrate (F-ND grains marketed by Atlantic Research Corp.) and binders made of epoxy resins and solvent or polybutadiene prepolymer/diisocyanate and solvent. Burning rates for the formulations tested varied from 2.5 to 28 cm/s. Rates over 18 cm/s proved to be excessive and ineffective in igniting the incendiary composition, while a rate of 12 cm/s was considered minimum to obtain ignition of the entire periphery in less than 3 s. From the compositions studied, a formulation was selected that contained the same binder as the incendiary composition and burned at an acceptable rate of 14.5 cm/s. This ignition composition was prepared from 10 parts by weight of binder (78% R-45HT and 22% DDI-1410) mixed with 20 parts of solvent (Dow Chemical chlorothene NU), with 60 parts by weight of ignition grains being added to this mixture.

6.0 FIELD PERFORMANCE OF THE INCENDIARY DEVICES

6.1 Tests at Energetex Engineering

During the course of development of the canister-type and peripheral-burning incendiary devices and at the same time as in-house testing, a program of field testing under simulated conditions was begun. The first such series of tests was carried out at the facilities of Energetex Engineering in Waterloo, Ontario and served to assess the potential of the two incendiary device designs for igniting varying thicknesses of different types of aged crude oil.

Prototype designs were dropped from an 11-m drop tower into 2-m x 2-m pools containing the aged crude. The devices were fired upon release from the drop tower and started to burn in the pool after a nominal 20-s delay. The canister-type device was able to ignite and promote the sustained combustion of a 2.5-mm thickness of one-week-aged Kopanoar crude, a 1.25-mm thickness of one-week-aged Weyburn-Midale crude and a 2.0-mm thickness of fresh marine diesel.

The peripheral-burning device also provided promising results for the ignition of crude. It was tested to a lesser extent in this series of tests, and was hand deployed onto the slicks. The device demonstrated the ability to ignite 3-mm slicks of one-week-aged Kopanoar crude, 2 mm of fresh marine diesel, and 1.5-mm slicks of one-week-aged Weyburn-Midale.

TABLE VII

Selected development tests at Energetex Engineering

Incendiary Device Configuration	Mix No.	Drop Height (m)	Oil Type	Oil Thickness (mm)	Delay/Burn Time of Device (min:s)	Slick Ignition (min:s)
canister	OP-42(1)	11	Kopanoar, one-week-aged	1.5	:22/2:00	partial only
"	42	9.5	"	2.0	:23/2:07	none
"	42	11	"	2.25	:25/1:53	partial
"	42	6	"	2.5	:23/0:49	slow (~ 1:00)
"	43(2)	11	"	2.5	--/1:50	rapid (~ :10-:30)
peripheral	42	0	"	3.0	:23/--	rapid
canister	43	11	Weyburn-Midale one-week-aged	2.0	:22/1:40	rapid
"	43	3	"	1.75	:21/1:56	rapid
"	43	11	"	1.25	:24/2:02	rapid
peripheral	42	0	"	1.5	:23/3:00	good (:30-1:00)
canister	43	11	Marine diesel, fresh	3.0	:24/2:05	rapid
"	43	4	"	2.0	:20/1:53	slow (~ 1:30)
peripheral	42	0	"	2.0	:22/2:31	slow (~ 1:00)

1- OP-42: formulation AM-78.

2- OP-43: formulation AM-79.

Table VII provides a summary of this series of tests. The slicks quickly started to burn locally (i.e. after some 0-20 s of preheating) but it would take from 1.0 to 1.5 min, in the estimation of the observers present, for the entire slick to undergo self-sustaining combustion. The incendiary devices continued to burn throughout this period until after the burns were judged self-sustaining.

6.2 Helicopter Drop Tests

Further tests were conducted in May 1980 at CFB Valcartier to examine the ease of handling and the behaviour of the devices during air deployment. Drops were made into the open water of Lac Laurier from a helicopter in a flight envelope of 10-20 m altitude and a forward speed of 15-30 knots. Additional drops were made from a 60-m altitude at a speed of 60 knots to simulate deployment from a slow-flying, fixed-wing aircraft.

No crude oil was used in these tests; rather, the tests served to determine the ability of the device to withstand water impact and function properly, and the ability of the crewman to hit a designated target area within the mentioned delivery parameters. The target consisted of a square, 10 m on the side, delineated by a log boom anchored in the centre of the lake. A summary of the test data is provided in Table VIII.

Both types of incendiary devices survived the air deployment and subsequent impact on water, sustaining no damage whatsoever. They came to rest essentially at the point of initial contact with the water, and the water disturbance brought about by the impact settled down well before the delayed ignition of the device took place. (The peripheral-burning device, however, skipped about 10 m on the water surface in the one case where it was deployed from 60-m altitude at 60 knots forward

TABLE VIII

Helicopter drops conducted at Lac Laurier, CFB Valcartier, 17 May 1980

Weather conditions: +10°C, sunny, winds calm

Helicopter Flight at Deployment		Type of Incendiary Device	Igniter Delay	Burn Time of Incendiary Device	Comments
Altitude (m)	Speed (knots)		(s)	(min:s)	
15	hover	canister	21	1:09	hit target
"	"	peripheral	--	--	landed just beyond target. Igniter functioned but ignition composition did not light (due to poor alignment)
15	15	canister	25	:50	hit target
"	"	canister	23	:33	hit target
"	"	canister	18	1:00	hit target in centre
"	"	peripheral	19	2:08	hit target in centre
15	30	canister	--	--	hit target. Igniter did not function
"	"	canister	21	1:07	hit target in centre
"	"	canister	20	1:21	hit target
"	"	peripheral	16	2:05	hit target in centre
60	60	canister	--	--	hit just before target. Igniter did not function
"	"	canister	18	1:02	hit just beyond target
"	"	canister	20	1:15	hit target in centre
"	"	peripheral	21	2:28	hit well before target (~ 20 m)

speed.) The crewman was able to hit the 100-m^2 target in all delivery modes attempted. With some practice, it was felt that a success rate approaching 100% would generally be achievable for hitting a target of this size within these delivery parameters.

Of the ten canister-type incendiary devices deployed, two failed to ignite because of a faulty firing mechanism. This was attributed to the poor design of certain components of the mechanism, and the solution to the problem was evident. Burn times for this model were rather short, averaging slightly over 1 min for the eight successful burns. The composition employed (50.5% $NH_4C\ell O_4$, 30% Mg, 19.5% binder; AM-79, OP-48,49) would have to be modified to yield a slower burning rate.

One failure was recorded for the four peripheral-burning incendiary devices tested. This was caused by failure of the ignition to transfer from the delay igniter to the ignition composition due to misalignment of the two. A refined assembly technique would eliminate this problem. The burn times for these devices were very acceptable, averaging over 2 min. The composition employed consisted of 56% $NH_4C\ell O_4$, 25% Aℓ, 1% thixotropic agent, and 18% binder (AM-77, OP-46,47).

6.3 Arctic Field Trials

In the winter and spring of 1980, a consortium of private interests, particularly Dome Petroleum, staged an oil-under-ice experiment in the Beaufort Sea at McKinley Bay, some 90 km northeast of Tuktoyaktuk, Northwest Territories (Ref. 14). The experiment consisted of approximately 6 m^3 of crude oil (a respectable quantity though still minute when compared to an actual oil spill) being pumped beneath the ice cover at three different times during the course of the winter. All aspects of the oil's subsequent movement and degradation were monitored up until and including its appearance on top of the ice cover the following spring. At that time various techniques for its containment and removal, particularly in-situ combustion, were demonstrated.

Through Environment Canada, DREV was provided with the opportunity to test its incendiary devices. This enabled scientists to realistically appraise the devices in conditions believed to simulate quite closely the aftermath of an undersea well blowout. Twenty canister-type and ten peripheral-burning incendiary devices were packaged and trucked to Whitehorse, Yukon Territory. From there they were flown to the spill site via Inuvik, N.W.T., as trucking routes north were closed at that time of the year (early June, when winter roads were impassable and summer roads not yet opened).

The incendiary devices were deployed either by hand or from a low-flying helicopter into contaminated pools considered large enough to be worth burning. Pool sizes varied from 5-100 m^2, though they generally tended toward the smaller of these sizes.

Results of these trials are given in Table IX with a typical pool ignition scenario involving the peripheral-burning incendiary device appearing in Fig. 9. A more complete summary of the DREV incendiary device Arctic trials can be found in Ref. 15. It is to be noted that the devices tested were manufactured in the same batch as those tested at CFB Valcartier. As a result the incendiary formulation remained the same, and some failures were again experienced in the firing mechanism of the canister-type device.

The most notable factor affecting performance of the canister-type device was the depth of the contaminated pools. These pools were shallower than anticipated, averaging only 2-5 cm in depth, and so could not provide the 10 cm of draught required for the canister device to float properly. As a result, they invariably ended up on their side burning in this manner, with only a portion of the heat output being

TABLE IX

Arctic field trials of DREV incendiary devices

Date	Device Type	Method of Release	Pool Area (m^2)	Miss Distance (m)	Igniter Delay Time (s)	Burn Time (min:s)
10 June	C	hand	7	-	misfire	--
10	C	air	5	0	N.R.	N.R.
24	P	air	6	10	N.R.	N.R.
24	P	air	6	0	N.R.	N.R.
24	P	air	3	0.4	N.R.	N.R.
24	P	hand	3	-	N.R.	N.R.
24	P	hand	6	-	N.R.	N.R.
26	C	hand	15	-	N.R.	N.R.
26	C	hand	5	-	24	N.R.
26	C	air	5	0	misfire	--
26	C	hand	5	-	N.R.	N.R.
28	C	air	37	0	misfire	--
28	C	air	4	0	22	:45
28	C	air	10	0	21	1:45
28	C	air	13	0	19	1:40
29	C	hand	10	-	20	1:45
30	C	air	7	1.5	N.R.	N.R.
30	C	air	16	0	20	1:32
30	C	air	7	0.8	22	N.R.
30	C	hand	7	-	20	1:45
2 July	C	air	70	0	17	1:20
2	C	air	70	0	20	1:10
2	C	air	12	1.2	20	1:15
2	C	air	12	0	16	1:45
2	C	air	10	1.5	20	1:35
5	P	air	10	2.5	N.R.	N.R.
5	P	air	6	2	N.R.	N.R.
5	P	air	5	3	N.R.	N.R.
5	P	air	6	0	N.R.	N.R.
5	P	air	10	0	N.R.	N.R.

C: canister-type device, mixes OP-48, 49, composition AM-79.

P: peripheral-burning device, mixes OP-46, 47, composition AM-77.

FIGURE 9 - Arctic field trials: hand deployment of peripheral-burning incendiary device

used to ignite the oil. Nevertheless the prototypes achieved pool ignition in all cases where they landed in contact with oil and functioned.

Of the twenty devices tested, three misfired because of the faulty firing mechanism. (These were later successfully refired and thrown back into the pools, though such a situation would not normally exist in an actual spill cleanup.) The remaining 17 devices functioned as designed with the firing mechanism providing delays of about 20 s prior to ignition, and the device burning for some 1 min 30 s on the average.

In view of the small pool sizes encountered, air deployment was difficult and required the helicopter to fly low (5-10 m altitude) and slowly (2-5 knots). Even at these conditions accuracy was only fair, with four misses recorded out of the 14 air drops attempted. Post-impact roll was minimal considering the solid ice cover and the shallowness of the pools. The major problem was in actually hitting the small pools from the air.

The peripheral-burning incendiary devices performed well; all devices functioned as designed with ignition delays and burn times (while not actually recorded) similar to those recorded at CFB Valcartier. Moreover, the shallowness of the pools presented no problem for this device. Owing to its design, the device required only a shallow draught and hence was generally able to float as anticipated. In the cases of very shallow pools (1-2 cm in depth), the device simply rested on the bottom of the pool where it functioned with no observable decrease in efficiency. All devices that landed in contact with the oil slick cover easily ignited it.

The major problem encountered with the peripheral-burning incendiary device was its postimpact roll following air deployment. With the hard ice cover and the small size and shallowness of the contaminated pools, the device tended to roll a fair distance from the point of initial contact and invariably ended up away from any oil contamination. As such, its effectiveness was diminished and future air deployment was not seen to be practical without correction of this problem.

7.0 SELECTION AND TESTING OF THE PREPRODUCTION MODEL

In consideration of the development tests and of the basic designs, it was generally considered that the canister-type incendiary device was slightly superior in performance to the peripheral-burning one. When floating in a pool the canister device has a low aspect above the surface and is very stable throughout the course of its burn. It provides a particularly intense source of heat, and is efficient in transferring this heat to the slick surface even under windy conditions. It could, however, be appreciably more expensive to manufacture than the peripheral-burning device, owing to its more intricate design.

The peripheral-burning device, on the other hand, is simple in design and is well-suited for mass production. Moreover it adequately fulfills the required role of the incendiary device, having demonstrated its ability to ignite combustible crude oil slicks that could possibly occur in the North. It requires little draught for proper operation, an important consideration in view of the shallow melt pools found during the Arctic field trials.

It was therefore decided at this stage to pursue development of only the peripheral-burning incendiary device. The exterior form of the device was altered to a square rather than round shape to alleviate the rolling problem encountered following initial contact with the ice cover. The incendiary composition remained unchanged from that employed in previous tests (56% $NH_4C\ell O_4$, 25% aluminum fuel, 18% binder and 1% thixotropic agent).

A preproduction contract of 200 devices was awarded to Aba Chemical Ltd. of Guelph, Ontario in the spring of 1981 in order to transfer the technology to the private sector and to provide necessary stores for further qualification testing. Of these, the first 22 devices were manufactured at DREV with contractor participation, while the remainder were manufactured by the contractor at his facilities.

7.1 Preproduction Proof Testing - CFB Valcartier

To verify the performance of the device, in particular the effectiveness of the square shape in eliminating postimpact roll, ten of the initial 22 devices were tested on frozen Lac Laurier, CFB Valcartier, in April 1981. Except for the absence of contaminated melt pools, it was felt that the solid ice cover (the snow having mostly melted) was representative of that found in the North during a cleanup operation and as such was a realistic test of the devices.

The devices were deployed from a helicopter flying at 15-m altitude and at a nominal airspeed of 20 knots. They were aimed at a small pyramidal marker on the ice, and the miss distance (the distance separating the marker from the final resting point of the device) was measured in each case. Results of this trial are to be found in Table X. It is noteworthy that the final two drops were made with the helicopter flying at a 30-m altitude and approximately 60 knots airspeed to simulate deployment from a fixed-wing aircraft as well as to test the structural rigidity of the device more rigorously.

Two misfires were recorded out of the ten devices tested. Subsequent investigation revealed that the glue used in the final assembly had failed to cure properly and hence provided an inadequate bond between the delay igniter and its polystyrene housing. This resulted in the delay igniter and the ignition composition becoming misaligned during firing, with interruption of the flame front taking place at that point. It was felt that increasing the contractor's familiarity with the assembly techniques involved and using a more appropriate glue would alleviate this difficulty and the problem was not given further attention.

Apart from the two misfires the incendiary devices functioned as designed, providing delays before ignition averaging about 20 s and burn times of over 2 min. The devices were sufficiently robust to withstand the landing impact on the hard ice cover without damage, particularly the final two drops made from a 30-m altitude at 60 knots.

TABLE X

Preproduction proof tests - Lac Laurier, CFB Valcartier - 12 April 1981

Test No.	Ignition Delay Time (s)	Burn Time (min: s)	Miss Distance (m)
1	misfire	--	6
2	15.7	2:20	6
3	22.7	4:15	6
4	misfire	--	4
5	22	2:24	6
6	16.8	3:21	2
7	20	2:26	8
8	20	2:21	0
9	19.3	2:28	30
10	17.9	2:11	15

Note: Tests 1-8 deployed at 15-m altitude and 15 knots airspeed.

Tests 9 and 10 deployed at 30 m and 60 knots.

The principal point of concern (that of postimpact roll) proved to have been largely resolved by making the shape of the device square. Roll distances ranged from 2 to 8 m on the ice surface, which is a fairly respectable figure considering the hard ice cover and the arduous launch conditions.

7.2 BIOS Experiment

A further ten devices from the initial batch were sent to Cape Hatt (Pond Inlet), N.W.T. for testing in conjunction with the Baffin Island Oil Spill (BIOS) experiment as igniters of stranded oil on Arctic shorelines.

While the majority are still being kept in on-site storage, three have been tested to date. Of these, one misfire has been reported, probably resulting once again from the use of an improper bonding agent during assembly, as discussed in Section 7.1. The remaining two devices were functioned on a beach onto which 1 cm of oil had been poured one hour previously and they burnt as designed. No ignition of the oil was observed, however. This was attributed to the fact that the oil had already seeped into the beach and was no longer in a combustible state.

7.3 Environmental Tests

To rigorously prove the design of the peripheral-burning incendiary devices as well as to confirm that the production version of the device conformed to specifications, 116 devices were drawn from the preproduction batch and subjected to environmental testing. These tests also served as a basis on which the Department of Energy, Mines and Resources could classify the incendiary device according to the Explosives Act, regulating its manufacture, transport, possession, and use.

A brief description of these tests follows, with the pattern of sequential testing appearing in Table XI. It is to be noted that the 12-m drop test is not included as part of the sequence as it was conducted as a separate test. Ideally, there should be no more than one failure after each stage of testing; all devices subjected to only one test should function as prescribed by the design specifications.

TABLE XI

Sequential test pattern of environmental tests

Environmental Test	No. of Items Sequentially Tested	No. of New Items Added to Test Lot	No. of Items Functioned
Hot Soak	60		12
Cold Soak	48	12	12
			12
Vibration	24	8	8
			12
Temperature and Humidity Cycling	12	12	12
			12
Rough Usage	12	12	12
			12
12-m Drop		12	(12)
		Total	116

High-low temperature conditioning (MIL-STD-810C, Method 501.1 and 502.1, Procedure 1): items are to be conditioned for 48 h at 70°C or for 24 h at -57°C and are then to be functioned at their soak temperature or alternatively at ambient conditions.

Vibration test: items are to be subjected to a vibration test comprising four separate periods of 7 h at a frequency of 50 Hz and an amplitude of 0.25 mm. The items shall then be inspected for damage and functioned at ambient conditions.

Temperature and humidity cycling test (Test 105.1 of MIL-STD-331): items shall be subjected to one 14-day cycle with temperature extremes of -55°C and 70°C, and a relative humidity level of 95% at the upper temperature limit. The items shall be examined and functioned at ambient conditions.

Rough usage test: items shall be placed loosely in a tumbling machine and tumbled for 15 min at the rate of approximately 12 r/min. No item shall function during the test and all items shall be safe to handle after testing. Items shall then be inspected for damage and functioned at ambient conditions.

12-m drop test: items shall be dropped free fall from a 12-m height onto a hard surface. To pass, items must not function during the test and must be safe to handle afterwards.

Results of the environmental testing program appear in Table XII. In general, an unacceptably high failure rate was observed, with 20 failures being recorded out of the 116 items tested. Most of these failures were directly related to inadequate quality control during production. It is to be hoped that such defects will not be present once the contractor is more familiar with the manufacturing techniques involved.

TABLE XII

Environmental testing of the peripheral-burning incendiary device

Environmental Test (Note 1)	Functioning Temperature	No. of Items Functioned	No. of Failures	Mean Igniter Delay (s)	Mean Burn Duration (min:s)	Failure Type (Note 4) A	B	C	D	E
Hot Soak	+70°C	6		18.1	1:41					
Hot Soak	ambient	6		20.0	1:40					
Cold Soak	-57°C	6	2	23.7	1:53	X				X
Cold Soak	ambient	6	1	19.2	1:42	X				
Hot, Cold	-57°C	6		22.9	1:59					
Hot, Cold	ambient	6		18.8	1:56					
Vibration (Note 2)	"	8	1	20.6	1:33		X			
Hot, Cold, Vib. (Note 2)	"	12		20.2	1:41					
T&H	"	12	3	20.5	1:33	XX		X		
Hot, Cold, Vib, T&H (Note 2)	"	12	7	20.5	1:38	XXX		XXX	X	
Rough	"	12	4	19.3	1:45	XXXX				
Hot, Cold, Rough	"	12	2	19.8	1:44	X			X	
Drop (Note 3)	-	(12)		--	--					
	Total/Average	116	20	20.2	1:43	12	1	4	2	1

Notes: 1 - All items contained in airtight polyethylene bags.
2 - Polyethylene bags removed for vibration and subsequent (if any) tests.
3 - Functioning is not a requirement of the drop test.
4 - Failure types: A - poor manufacture of firing mechanism
B - polycarbonate firing pin
C - faulty primer cap
D - misalignment of delay igniter with ignition composition
E - insufficient output of delay igniter

Failure type A resulted from the presence of burrs on the polycarbonate striker formed during moulding, leading to a friction or interference fit inside the phenolic housing. The striker was consequently not able to impact the primer cap with sufficient force to bring about its firing, leaving instead only a slight indentation in the latter.

Failure type B also results from poor quality control, with the firing mechanism being assembled using a striker that did not embody a steel firing pin. No signature was observable in the primer cap following testing.

The above two failure types account for 13 of the recorded misfires; in all cases the delay igniters were reassembled into proper firing mechanisms and functioned as designed. A further four delay igniters, however, did not function even after this second attempt. These were therefore identified as failure type C, with the primer caps being at fault. It is to be noted that these failures occurred with devices that had been temperature and humidity conditioned, in particular where the polyethylene bags were not present. Visual inspection of these and other delay igniters revealed that the lacquer seal was not always sufficient and a hermetic seal is of paramount importance to prevent moisture from penetrating and degrading the primer cap. In addition, radiographic inspection revealed that some primer caps were not fully seated; excessive vibration could therefore dislodge the primer cap and break any seal that might otherwise be present.

Failure type D is a result of the polystyrene pads, particularly the one housing the firing mechanism, becoming detached from the remainder of the incendiary device because of inadequate bonding (the AF/P described in Section 5.2 was used by the contractor during assembly). The delay igniter consequently became misaligned with the peripheral ignition composition, and the ignition sequence was interrupted at this point. The problem was more serious than the two failures would indicate, as a total of 10 of the 116 devices tested showed at least one of the floatation pads becoming separated. The majority of these ten devices would have constituted failures had they been deployed as intended rather than being placed on the ground and fired as during these tests. Apart from possible ignition failure, if a device was to land on a slick surface with no floatation pad on the underside, the incendiary composition would be positioned beneath the surface and its combustion would be thermally quenched. It is recommended that the AF/P be used more liberally or a suitable replacement glue be employed for any further production.

One further isolated failure, designated type E, was observed during the testing program. In this case all components appeared to be correctly assembled, but the ignition sequence was not transferred from the delay igniter to the peripheral ignition composition. The failure was blamed on an insufficient output from the delay igniter to ensure propagation of the flame front.

A reexamination of all failures reveals that improved manufacturing techniques should completely eliminate failure types A, B, and D, and hopefully reduce the number of remaining failures. On this basis, therefore, a subsequent production run should yield very reliable and effective incendiary devices.

One further aspect demonstrated by the preproduction devices requires careful attention. During functioning, all devices were observed to burn vigorously for the first 40 s; the burn then gradually tapered off to provide a total duration of about 1 min 45 s. Aside from being shorter than the desired 2 min, a burn of this nature is not advisable. A too-large combustion surface was thought to be the cause of this shorter burn; rather than burning uniquely around the periphery and propagating radially inwards, it was suspected that the combustion front was also progressing via the plywood/incendiary composition interface.

In a subsequent study at DREV, devices were produced duplicating the technique in which they had been manufactured by the contractor (i.e. the second method described in Section 5.2 and Fig. 7). It was shown that if an insufficient amount of adhesive was used in bonding the plywood disc to the slab of incendiary composition, the combustion was overly vigorous at the start and a short burn time resulted. If, however, the incendiary composition was coated liberally and completely with adhesive when bonding the plywood disc, surface combustion was avoided and a normal burn was achieved. Devices manufactured by the contractor were subsequently dismantled and showed that, even though a strong mechanical joint had been formed between the incendiary composition and the plywood disc, much of the interface was not covered with glue. This would therefore give rise to the unwanted surface combustion.

Alternatively, further devices were manufactured employing the third method described in Section 5.2 and Fig. 7. The incendiary composition was cast directly between the two plywood discs, and since it was vulcanized in place, no voids were present in the plywood/ incendiary composition interface. Consequently there was no possibility of combustion on the surface of the slab of incendiary composition; rather, it burned uniformly at its periphery and burn durations averaging 2 min 10 s were attained. It is recommended that this technique be employed for any future production of the incendiary device for two reasons:

a) it is superior from the processing point of view, resulting in a simplified, faster, and hence more economical production; and
b) it provides more reliable performance as a superior bond between the plywood discs and incendiary composition slab is generally achievable, assuring the peripheral-burn mode at all times.

8.0 CONCLUSIONS

Two different designs of an incendiary device for the in-situ ignition and combustion of confined crude oil slicks have been developed and tested at DREV. Patent applications for both designs have been filed in Canada and the United States. Of the two prototypes, development of the peripheral-burning incendiary device has been carried through to the preproduction stage, including the transfer of its production techniques to the private sector. Consequently the goal of making a proven safe, reliable, and effective air-deployable incendiary device commercially available for use in the event of an Arctic oil spill has been achieved.

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