ARCTIC RESPONSE TECHNOLOGY
OIL SPILL PREPAREDNESS

January 20, 2016
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HISTORICAL REVIEW AND STATE OF THE ART FOR OIL SLICK IGNITION FOR ISB

ARCTIC OIL SPILL RESPONSE TECHNOLOGY – JOINT INDUSTRY PROGRAMME

The oil and gas industry has made significant advances in the ability to detect, contain, and cleanup oil spills in arctic environments (Potter et al., 2012). Ongoing research continues to build upon more than fifty years of examining all aspects of oil spill preparedness, oil spill behaviour, and available options for oil spill response in the Arctic marine environment. This research has included hundreds of studies, laboratory and basin experiments and field trials, conducted in the United States, Canada, and Scandinavia. To build on existing research and improve technologies and methodologies for arctic oil spill response, members from the IPIECA-Oil Spill Working Group, the Industry Technical Advisory Committee (ITAC) and the American Petroleum Institute-Emergency Preparedness and Response Programme Group formed a joint committee in 2009. The committee's task was to review the oil and gas industry's prior and future work scope on prevention and response to oil spills in ice in order to identify and prioritise technology advances and research needs. One outcome was the recommendation to establish the Arctic Oil Spill Response Technology Joint Industry Programme (JIP) that would undertake targeted research projects identified to improve industry capabilities and coordination in the area of arctic oil spill response.

The JIP was launched in January 2012 and over the course of the programme is carrying out a series of advanced research projects in six key areas: dispersants, environmental effects, trajectory modelling, remote sensing, mechanical recovery, and in situ burning (ISB).

TABLE OF CONTENTS

FIGURES

TABLES

INTRODUCTION

This review summarises the technologies available for initiating in-situ burning (ISB). The focus of the report has been on oil spill igniters reported in the available open literature, which encompasses North American and European research and development efforts. The authors are not aware of any literature on oil spill igniters in Russia or Asia, other than reports of using ad-hoc ignition techniques (oily rags, torches, fuel oil in containers, etc.) during actual spill responses in these areas. Much of the technology was conceived as a result of ISB attempts at specific spill incidents. For example, the *Torrey Canyon* incident in 1967 prompted considerable research on both sides of the Atlantic on the subject of oil slick ignition. Table 1 lists the 60 or so spills (both accidental and experimental) that have provided a basis for the present knowledge of oil spill in-situ burning in ice-affected waters. The most detailed information has been derived from laboratory tests and the mesoscale tests noted.

Table 1. SUMMARY OF IN-SITU BURNING: TESTS AND USE ON SPILLS ON WATER AND IN ICE-AFFECTED WATERS

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
1958	Pipeline spill in Mackenzie River	Spill was boomed with logs and burned.	Crude	Burn was successful
1967	Tanker accident *(Torrey Canyon)*	Attempts were made to burn oil on water with bombs, napalm and other materials.	100,000 tonnes of crude	40,000 to 50,000 tonnes of oil burned on ship.
1969	Holland	Series of experiments. Igniter Kontax tested.	Crude	Proved the possibility of burning slicks.
1969	Cargo ship *Eiva* sank releasing oil in Gulf of Finland	0il burned on shores and bays using paraffinic oil as primer.	15 tonnes of diesel fuel.	Burn was reported to be successful.
1969	Tanker *Raphael* went aground off Finland	Peat moss, fuel oil and petrol used.	60 tonnes of crude.	90% of oil was burned.
1970	Accident in Deception Bay, Quebec	Tank farm accident caused by slush avalanche. Onshore spill reached intertidal ice.	1500 tonnes of diesel and gasoline spilled.	Oil pumped to Ice surface and burned; some oil on ice, and contained by near shore ice also burned
1970	Accident in Chedabucto Bay *(.Arrow)*	Some isolated slicks were burned using Seabeads. Varsol also used as primer. Oil on shoreline was ignited and burned with napalm and a flame thrower.	Bunker C, approx. 16,000 tonnes.	Mixed results.
1970	Vessel collision in Tralhavet Bay, Sweden, March *(Othello and Katelysia)*	Spill was trapped in pack ice and a silica wicking agent (Cab-O-Sil ST-2-0) was used to burn. Conditions precluded mechanical containment and recovery.	Between 52,000 and 90,000 tonnes of Bunker C spilled.	Good results reported.
1972	Diesel fuel spill in ice-choked river in Sweden	Sorbent product Saneringsull used as wicking agent.	600 tonnes of diesel fuel oil.	400 tonnes burned.
1973	Canada	Rimouski experiment	Crude	Demonstrated high removal rates possible, >75%.
1974-75	Experimental spill, Balaena Bay, Canadian Beaufort Sea	Oil spilled under ice was burned in spring as It accumulated in melt pools on the ice surface.	45 tonnes of crude.	Highly successful burns; proved the effective use of burning oil in ice.
1976	Tanker *Urquiola* went aground off Spain	Oil burned accidentally over 3-day period.	100,000 tonnes of light Arabian crude.	
1976	Accident In Lake Huron *(Imperial St. Clair)*	Oil became incorporated In ice, and numerous burns conducted as oil melted out of ice. Oily rags used as igniters.	Diesel and gasoline, 220 tonnes spilled.	80-95% of the oil burned.
1976	Tanker *Argo Merchant* went aground off Nantucket	Tullanox 500, primed with JP-4, used as igniter.	28,000 tonnes of No. 6 Fuel.	Not able to burn slicks on open water.

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
1976-79	Experiments in Canadian Arctic	Various tests on parameters controlled burning.	Crudes	
1977	Barge *(Bouchard* #65) accident In Buzzards Bay, Massachusetts	A pool of 950 liters in broken ice was ignited with Tullanox/JP-4 igniters dropped from helicopter.	No.2 fuel oil, 300 tonnes spilled.	15 tonnes burned.
1979	Tank collision *(Atlantic Empr68* and *Aegean Captain)* in Caribbean Sea	Two fully laden VLCCs collided leading to oil burning on water.	288,000 tonnes of crude.	Virtually all oil burned.
1979	Accidental burn of grounded *Burmah Agate,* Galveston, Texas	Oil burned on the tanker and on water.	Nigerian crude and blend, 40,000 tonnes.	74% of oil burned.
1979-80	Experimental release	Oil release with air under first-year sea ice to simulate blowout under ice.	Prudhoe Bay crude, 20 m^3.	
1980	Tests at Port Mellon, B.C.	Static test of Dome Petroleum's stainless steel fire-resistant boom with burning crude oil.	Redwater crude oil, 1.5 m^3.	
1980	Cargo vessel *Edgar Jourdain* went aground In NWT in ice conditions in September	Oil burned after ice melted.	50 tonnes of marine diesel fuel.	Successful burn.
1981	Tests at EPA OHMSETT test tank	Test of Dome Petroleum's boom with burning crude oil and waves in test tank (22 tests).	Circa 4X light oil and Murban crude.	
1981	Canada	McKinley Bay experiment.	Crudes	Noted difficulty In burning emulsions.
1983	Storage tank leak into Warwick Lake, Ontario in January	Oil pumped to ice surface and burned over winter and following spring.	59 tonnes of diesel fuel oil.	85% burned.
1983	Tanker *Honam Jade* goes aground off South Korea	Uncontained 3-km diameter slick set afire; oil burned for 2 hours; residue sunk.	2000 tonnes of Arabian Heavy crude oil.	Successful intentional burn of large, uncontained spill.
1983	Tier 2 burn test in Prudhoe Bay test pit (Task 1)	Four tests conducted with uncontained oil spilled in broken ice conditions.	Circo 4X light oil and Murban crude.	55%- 73% of oil burned.
1983	Tier 2 burn tests in Prudhoe Bay test pit (Task 2)	Burning of oil inside fire-resistant boom in test pit (single burn and continuous burn); follow-up tests conducted in test tank.	Single burn: 34 gal. fresh, degassed Prudhoe Bay crude. Continuous burn: 1 hr @ 2.5 gpm.	72% -88% of oil burned.
1984	Experiments at OHMSETT (New Jersey)	4 tests were run in EPA test tank.	Prudhoe Bay crude (fresh and weathered).	
1984	Canada	Series of experiments.	Several	Uncontained burning only possible in few conditions.
1985-1989	Various small-scale tests	National Institute of Standards and Technology tests to study combustion and smoke generation.	Alberta Sweet, Murban, Prudhoe Bay	Comprehensive analysis of physics and fate of burn products.
1986	Canada	Ottawa experiment/analysis.	Various	Analysis shows PAH's about same in oil and residue.
1986	Experiments at OHMSETT (New Jersey)	Test in EPA test tank.	Prudhoe Bay and Hibernia crudes.	
1986	Experimental spills off Nova Scotia	Two spills each 1m^3 ignited after several hours spreading in pack ice.	Alberta crude.	
1986	ACS Deadhorse Helitorch tests	Tests of ignition of crude oil in test pans using a Helitorch	Fresh and weathered crude oil (20 L/pan)	Tests confirmed the ability to ignite oil with a Helitorch.
1986	Calgary,Alberta	25 tests in Jan. and Feb. at the Esso Research Ice Basin to test burning in ice leads (2 experiments	Aged Normal Wells crude.	

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
		in brash ice).		
1988	Experimental spill off Spitsbergen	100 m of 3M Fire Boom used to contain slick, which was ignited with Helitorch	Statfjord crude, 2m^3	Successful burn in a towed U-boom configuration 95% burn efficiency.
1988	St. Vincent's Bay, B.C. spill	Burning of spilled diesel on water; winter.	9 tonnes diesel spilled.	
1989	Test burn in Prince William Sound during *Exxon Valdez* spill	150 m of 3M Fire Boom towed by 2 vessels to collect oil and contain It for burning; the oil had been floating on calm water for 30 to 40 hours before it was burned.	Prudhoe Bay crude, approx. 60 to 120 tonnes.	98% burn efficiency in fire boom collected oil. Residue of stiff, taffy-like oil.
1990	Rivers Inlet, B.C.	Fuel burned on water.	Approx. 85 tonnes fuel.	Efficient removal; noted need for experienced personnel.
1990	ACS test burns	Purpose was to test 3M Fire Boom for a 48-hour burn.	Prudhoe Bay crude.	
1990	Tanker accident *(Mega Borg),* Gulf of Mexico	Fire from series of onboard explosions 00 tanker.	Palanc Angola crude, 15,000 tonnes.	Estimated 51 % burned and about 27% evaporated.
1990	Tanker accident *(Haven),* Gulf of Geneva, Italy	Fire from series of onboard explosions within 500 m of populated area.	Iranian heavy crude, 144,000 tonnes.	3-day fire consumed most oil.
1991	Tanker accident *(Aegean Sea),* La Coruna, Spain	Fire from onboard explosions within 500m of populated area.	Brent crude.	24 hours burn –smoke, evacuated approximately 100 houses near harbor.
1991	Oil well blowout off Louisiana	Oil contained by conventional boom was Ignited and burned; boom was destroyed.		
1991-2000	Test burns in Mobile, Alabama	Mesoscale tests in water-filled test tank with crude and diesel slicks up to 15m in diameter inside fire-resistant boom. NIST	Louisiana crude.	Comprehensive analysis of physics and chemistry of burning and fire boom performance.
1991-1994	Field experiments on Svalbard	Mid-scale tests of burning crudes and emulsions on ice/ simulated pack ice contained and uncontained	Statfjord crude.	Advanced knowledge of emulsion burning, enhanced igniters for emulsions
1993	Test burns off Newfoundland	Two burns of boomed oil, 29 m^3 and 48m^3.	Alberta Sweet Mix Blend crude oil.	Detailed results on fate and chemistry of the burn products.
1993	Maine tank farm release into ice and snow-covered pond and wetland	Oil unreachable by vacuum trucks was burned.	JP-5	98% of remaining oil removed by burning.
1994	Test tank experiments in Alaska	Mid-scale experiments on burning emulsions and collecting soot plume data.	Alaska North Slope crude.	Successful burns with emulsion breakers in fire boom on test pond.
1996	Offshore burn test with fire boom in UK	Full-scale test of emulsion-breaking igniter on 25% water emulsion in fire boom.	Larkwhistle Farm crude.	EB igniter successfully lit emulsion in boom.
1998-2002	Fire boom testing at Ohmsett	Testing of fire booms using ASTM methods with propane.	Propane fire simulator.	Six fire booms and blankets tested.
1999	*New Carissa* aground off Oregon coast	On board ignition of spilled bunker fuel.	Four different bunkers.	Oil burned in hulk.
2006-2008	Experimental burns of oil on ice at Svalbard	Oil released in ice sheet in spring ignited and burned.	Statfjord crude.	96% removal efficiency.
2008	Experimental burns of oil in pack ice in Barents Sea	Field tests of herders in drift ice.	Heidrun crude.	90+% removal of herded slick.

DATE	TYPE/LOCATION	DESCRIPTION	TYPE	RESULTS
2009	Experimental burns of oil in pack ice in Barents Sea	Field tests of fire booms in drift ice (trace and 3 to 5 tenths) and burning in 7-9/10ths close pack.	Troll B crude.	90% removal of contained slicks.
2010	Deepwater Horizon	Use of controlled burning with fire booms in response to deep water blowout.	MC-252 crude	411 oil collection and ignition attempts; 376 burns that removed 220,000 to 310,000 bbls.

Over the intervening 50-year period a greater understanding has developed of the processes involved in the ignition, steady burning, vigorous burning, and extinction phases of in-situ combustion, and this has led to a refinement of existing ignition equipment and new tools and techniques. The recent *Deepwater Horizon (*Macondo) response has already generated a new round of technological refinements and operational guidelines for open-water burning of oil. Additional details on these spills may be found in the IOGP Arctic JIP Report, *In Situ Burning in Ice-Affected Waters: State of Knowledge* (http://www.arcticresponsetechnology.org/wp-content/uploads/2013/10/Report-7.1.1-OGP_State_of_Knowledge_ISB_Ice_Oct_14_2013.pdf)

The purpose of this review is to provide technical guidance for the development of an oil-slick ignition system to be combined with a recently developed herding agent application system for helicopters. The system is to be designed so that a single helicopter can first contract and later ignite and burn oil slicks without the need for booms or surface vessels. The concept of contracting slicks in open water and in drift ice conditions with herding agents and then igniting them offers the possibility of a rapid aerial response to spills.

CHAPTER 1. OIL SLICK IGNITION

Ignition involves two components: heating the floating slick to a temperature high enough such that the liquid hydrocarbons are vaporizing quickly enough to generate a concentration in the air layer above the slick that will support burning (the Lower Flammability Limit or Lean Flammability Limit), and then providing ignition energy to initiate burning. The temperature at which a slick produces vapours at a sufficient rate to catch fire is called the Flash Point. At a temperature called the Fire Point, which is a few degrees above the Flash Point, the oil is warm enough to supply vapours at a rate sufficient to support continuous burning (Kanury 1988).

An important objective of in-situ burning of oil is to ignite the maximum possible area of the slick. Ignition of an oil slick and subsequent flame spreading are strong functions of the temperature of the slick, its volatility, its degree of emulsification, and the location of the ignition on the slick relative to the wind. If oil is at a temperature above its Flash Point, ignition is simple and flame propagation is normally rapid; otherwise, ignition and flame spreading can be slow and difficult.

For an oil slick on water at a temperature below its Flash Point, an igniter must heat the adjacent slick to above its Flash Point. This problem involves two aspects: heat transfer through the slick and convective motion effects induced in the heated slick (Figure 1). When an oil slick on water at a sub-flash temperature is exposed to a radiant heat/ignition source initially, the surface of the slick is heated. As soon as this happens, the warm oil (with a lower air/oil interfacial tension than the colder, underlying oil) begins to flow horizontally away from the heat source. Its place is taken by colder fuel rising up from beneath in convection-induced, gravity-driven flow. It has been shown that this convective flow is decreased with increasing oil viscosity and decreasing bulk oil surface tension (Murad *et al.* 1970); thus, more viscous oils (all other factors being equal) are easier to ignite. In any case, as heated oil is flowing outward, heat is also simultaneously conducted and convected vertically through the oil slick to the underlying water. If the slick is sufficiently thick to insulate itself and allow the surface layer to heat to its Flash Point, the slick will start to burn in the vicinity of the igniter.

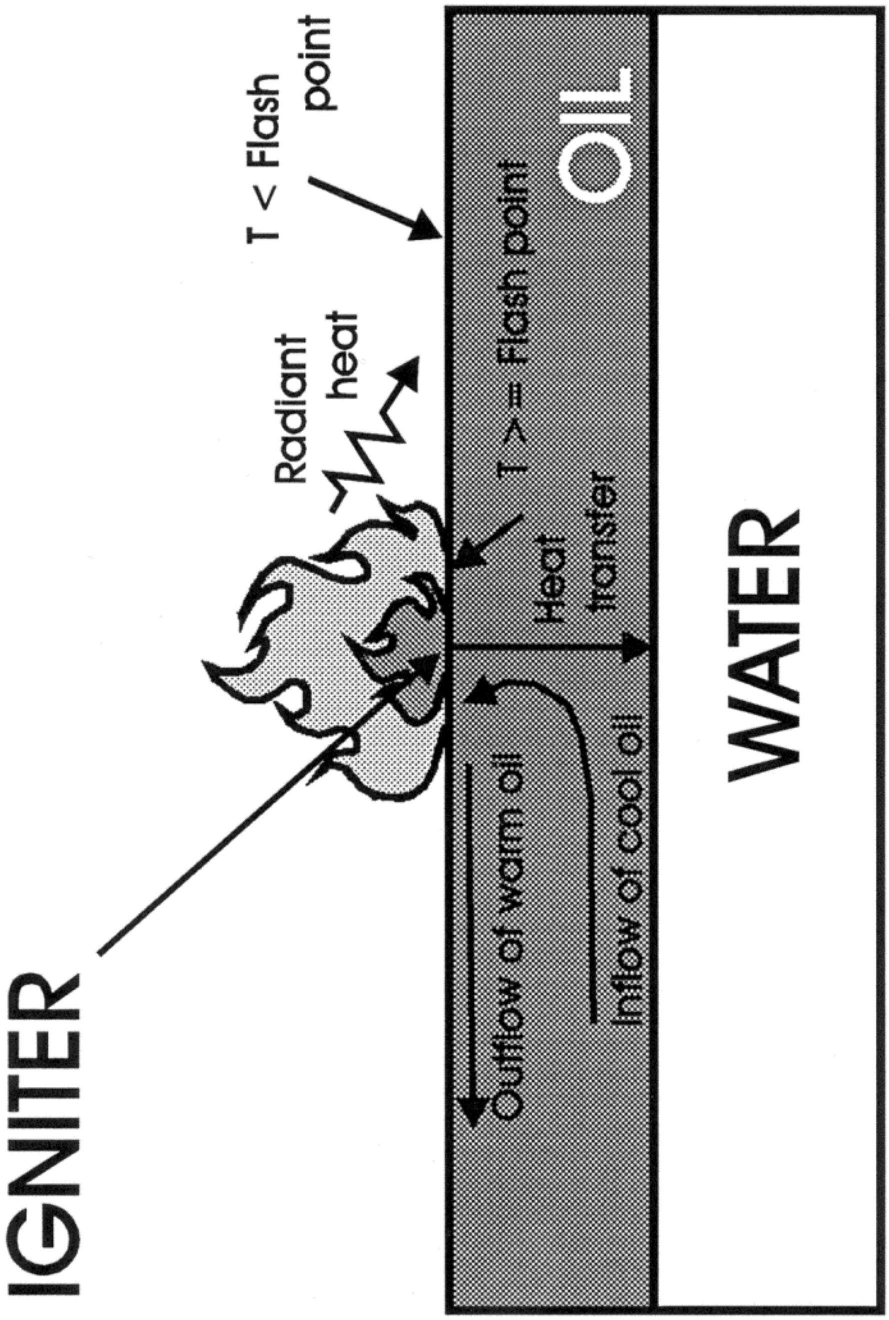

Figure 1 Heat transfer and convective motion during slick ignition (source: Marine Spill Response Corporation)

Extensive experimentation with a variety of oil types, igniters and environmental conditions (Maybourn 1971, Energetex 1978 and 1980, Allen 1987, S.L. Ross 1989, Bech *et al.* 1993) has confirmed the following "rules-of-thumb" for the ignition of oils on water in relatively calm, quiescent conditions:

Ignition Rules of Thumb

- The minimum ignitable thickness for fresh crude oil on water is about 1mm;
- The minimum ignitable thickness for aged, unemulsified crude oil and diesel fuels is about 2 to 5mm;
- The minimum ignitable thickness for residual fuel oils, such as IFO 380 (aka Bunker "C" or No. 6 fuel oil) is about 10mm; and,
- Once 1 m^2 of burning slick has been established, the fire can sustain itself without an external heat source.
- Emulsion slicks having stable water contents of 25% or more are generally unignitable. Some crudes form meso-stable emulsions that can be ignited at much higher water contents. Paraffinic crudes appear to fall into this category.

Note that although thick residual fuel oil slicks have been found to be ignitable, it is likely that efficient burning of a large spill of residual oil in-situ will be extremely difficult unless promoters like diesel are first spread on its surface to enhance flame spreading.

The maximum ignitable water content of an emulsion seems to be controlled by three factors:

- degree of weathering of the parent oil (more evaporated emulsions are more difficult to ignite);
- stability of the emulsion at temperatures less than 100°C (Cabioc'h 1993 postulates that high asphaltene emulsions are more difficult to ignite); and,
- strength of the igniter.

The maximum ignitable water content for oils has ranged from 10% to 70% (Energetex 1980, SL Ross 1989, Bech *et al.* 1992, Cabioc'h 1993, Guenette *et al.* 1994, SL Ross 1997, Fritt-Rasmussen *et al.* 2011). Guenette *et al.* (1994) showed that emulsions with water contents as high as 50%, when herded into a contained oil slick fire by current and wind action, would ignite and burn efficiently. This was also observed during burn operations at the Macondo response (Mabile 2010).

Not only are water-in-oil emulsions difficult to ignite, flame spreading over their surface is much slower. Energetex (1980 and 1981), Hossain and Mackay (1981), Smith and Diaz (1987), SL Ross (1989), Allen (1991), Bech *et al.* (1992) Guenette *et al.* (1994) and SL Ross (1995 and 1997) and Wu *et al.* (1997) have all noted significant reductions in flame spreading rates with increasing water content. This is likely due to a combination of the following factors:

- increased slick viscosity, slowing interfacial-tension-induced flow and flame spreading;
- increased heat transfer by conduction through the emulsified slick;
- increased Flash/Fire Points of the emulsified slick; and
- delays due to the need to break the emulsion and form a layer of water-free oil for the flame to propagate across.

Aside from oil type and thickness, other factors can affect the ignitability of oil slicks as well. The key parameters are:

- wind speed; and

- igniter strength.

Secondary factors include:

- ambient temperatures; and
- waves.

The effects of wind speed on the ignitability of oil slicks have been studied both theoretically and experimentally. Murad *et al.* (1970) developed a mathematical model showing how the wind decreases the volume of ignitable vapours above the slick. Wind speed also reduces the ignitability of oil slicks at sub-flash temperatures possibly by increasing convective heat and mass transfer at the oil/air interface.

In tests with solid propellant igniters, Energetex (1981) reported that, in an 8 m/s wind created by a fan adjacent to the slick (equivalent to an 11 m/s wind measured at a 10 m elevation) ignition of weathered crude and marine diesel slicks was not possible, even with slick thicknesses of 10 mm. For fresh crude oil a 2 mm slick was ignitable in a 3 m/s wind but not in an 8 m/s wind (equivalent to 11 m/s @ 10 m): the minimum ignitable thickness for fresh crude in an 8 m/s (11 m/s @ 10 m) wind was 5 mm. Allen (1987) reports that winds of 3 to 5 m/s did not affect slick ignition with small (60 to 120 mL) blobs of gelled gasoline; but, winds of 8 m/s required the use of 250 to 500 mL blobs to effect ignition. The maximum wind speed for successful ignition for large burns has been estimated as 10 to 12 m/s (Bech *et al.* 1993*,* Cabioc'h 1993).

Wave action can prevent ignition of marginally ignitable slicks (Tam and Purves 1980, Energetex 1981, Bech *et at.* 1993). Energetex (1981) reports that the minimum ignitable thickness for one week aged Prudhoe Bay crude increased from about 3 mm in a 5 m/s wind to 10 mm with the application of 10 cm high waves. This is believed to be due to forced convection heat transfer induced by the waves making it more difficult for the igniter to heat the surface of the oil slick to its Flash Point.

Ambient temperature can also affect slick ignitability. If an oil slick is at a temperature above its Flash Point it will ignite rapidly and easily; however, oil slicks at sub-flash temperatures are more difficult to ignite. Ambient temperature has a greater effect on flame spreading velocity than on ignition, as discussed in the next section.

1.1 Flame Spreading

Flame spread is a crucial aspect of effective in-situ burning; if the fire does not spread to cover a large part of a slick, overall removal efficiency will be low. Flame spreading can be divided into two distinct categories: sub-flash spreading and super-flash spreading with an intervening transition zone characterised by pulsating spread. The dependence of flame spreading velocity on liquid temperature is shown in Figure 2 (Akita 1972) for methanol. At temperatures above the fluid's Flash Point, flame spreading is controlled by vapour phase effects. As the temperature rises from the Flash Point to the stoichiometric temperature (the liquid temperature required to produce vapour at a rate allowing combustion of stoichiometric amounts of fuel and oxygen) the flame spreading velocity increases from the laminar flame burning velocity at the lean flammability limit to a maximum that is on the order of the laminar flame burning velocity for a stoichiometric mixture of fuel vapour and air. For sub-flash fuel temperatures, the flame spreading velocity seems to be controlled by liquid- phase heat and mass transfer phenomena.

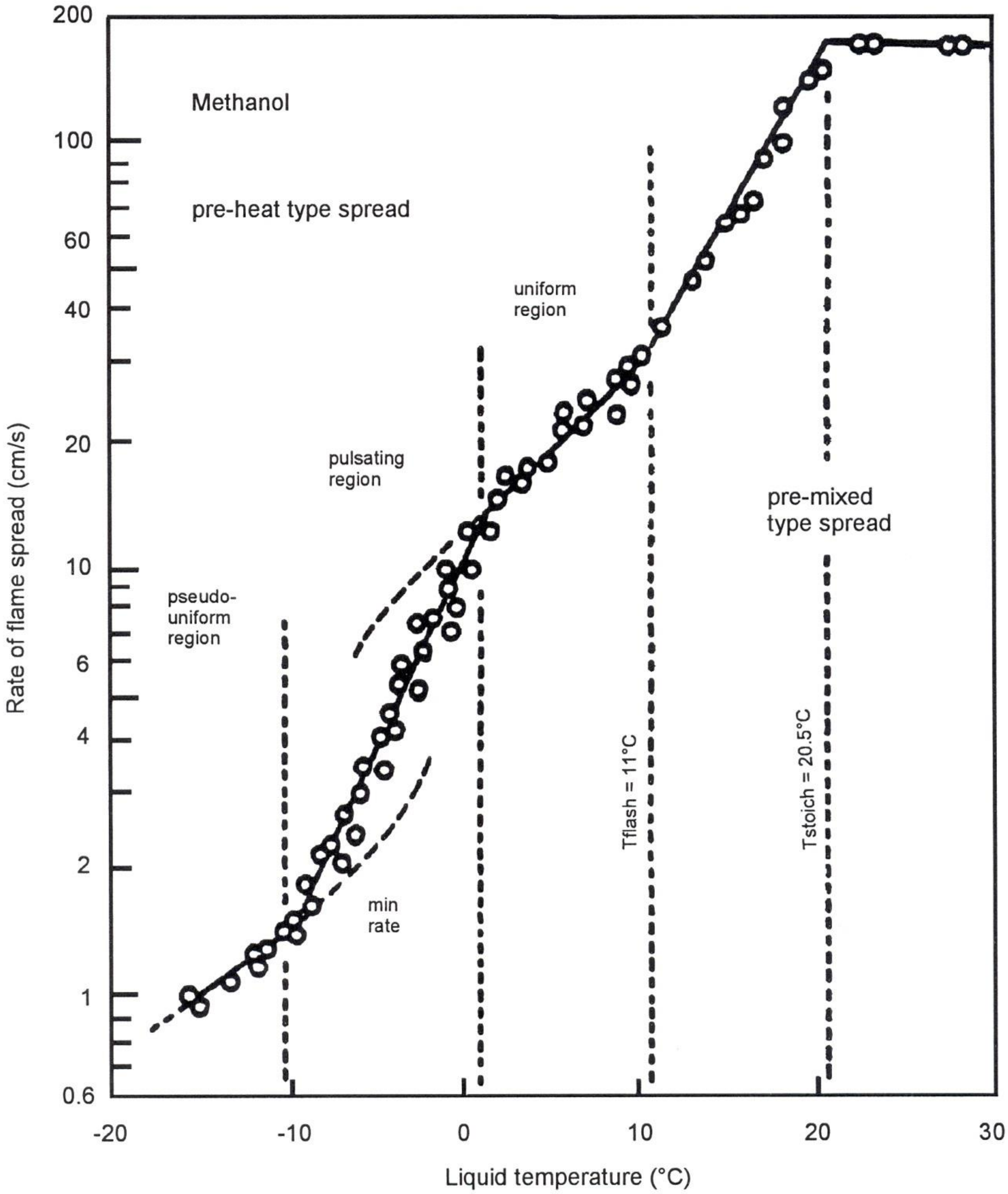

Figure 2 Relationship between the liquid temperature and the rate of plane flame spread of methanol in a vessel 2.6 cm wide and 1.0 cm deep. (source: Marine Spill Response Corporation)

Starting at a temperature well below the Flash Point (say -20°C on Figure 2) the flame spreading is controlled by the rate at which cold fuel in front of the flame is warmed by the advancing flame front. There are two mechanisms by which heat is conducted from the flame to the cold fuel: radiation and convective flow (Glassman *et al.* 1968, Sirignano and Glassman 1970, Mackinven *et al.* 1970, Akita 1972). In the early stages of fire spreading over a sub-flash fuel on water, it is the convective flow process that dominates; for larger fires, the radiation of heat dominates

(Mackinven *et al.* 1970). Figure 3 shows a schematic cross-section of an advancing flame that illustrates the processes involved for a quiescent sub-flash situation.

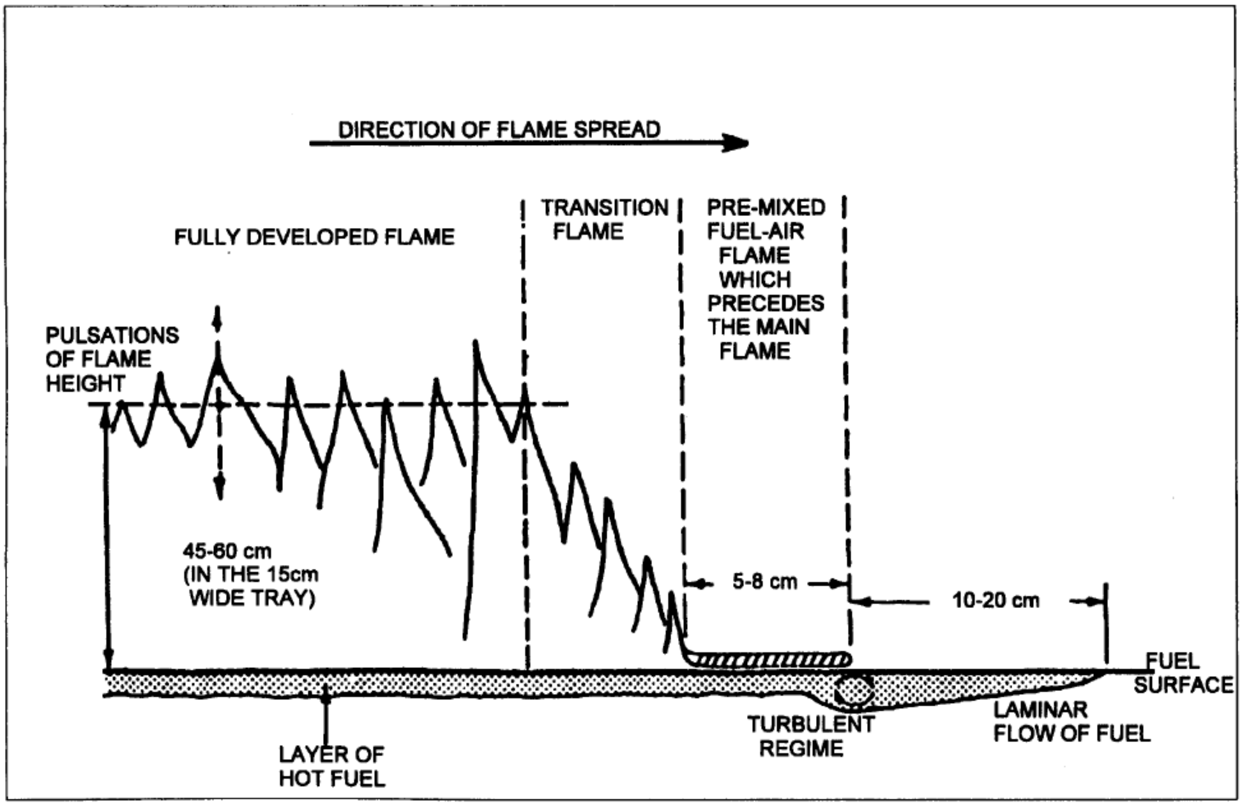

Figure 3 Schematic representation of the spreading flame (source: Marine Spill Response Corporation)

For small fires, and in the early stages of a larger fire, fuel underneath the leading edge of the flame front is hotter than the unignited fuel; as such, the hot fuel has a lower interfacial tension than the cold fuel and tends to flow forward over it (Mackinven *et al.* 1970, Glassman *et al.* 1968, Torrance and Mahajan *et al.* 1974). This is called the Marangoni effect. This interfacial tension flow outwards sets up a return flow of cold oil beneath the warm layer. Additionally the combustion process itself sets up a bulk inward flow towards the fuel (Torrance and Mahajan 1974). Further resistance to the interfacial flow is provided by viscous dissipation in the warm fuel layer itself (Glassman and Hansel 1968, Glassman *et al. 1969).* Figure 4 shows the dependence of flame velocity on fuel viscosity for a slick of kerosene at temperatures 40°C below its Flash Point (Glassman *et al.* 1969). It is interesting to note that the flow-dissipating effects of increased viscosity aid in ignition of oil, but detract from subsequent flame spreading.

As the bulk temperature of the warming fuel approaches the Flash Point on Figure 3, the flame begins to pulsate. This pulsating region is characterised by a thin, blue "pre-mixed" flame travelling ahead of the yellow "diffusion" flame front. Akita (1972), Glassman and Hansel (1968), and Mackinven *et al.* (1970) state that for hydrocarbon fuels this pulsating flame relates to the difference between the Flash and Fire Points of the fuel.

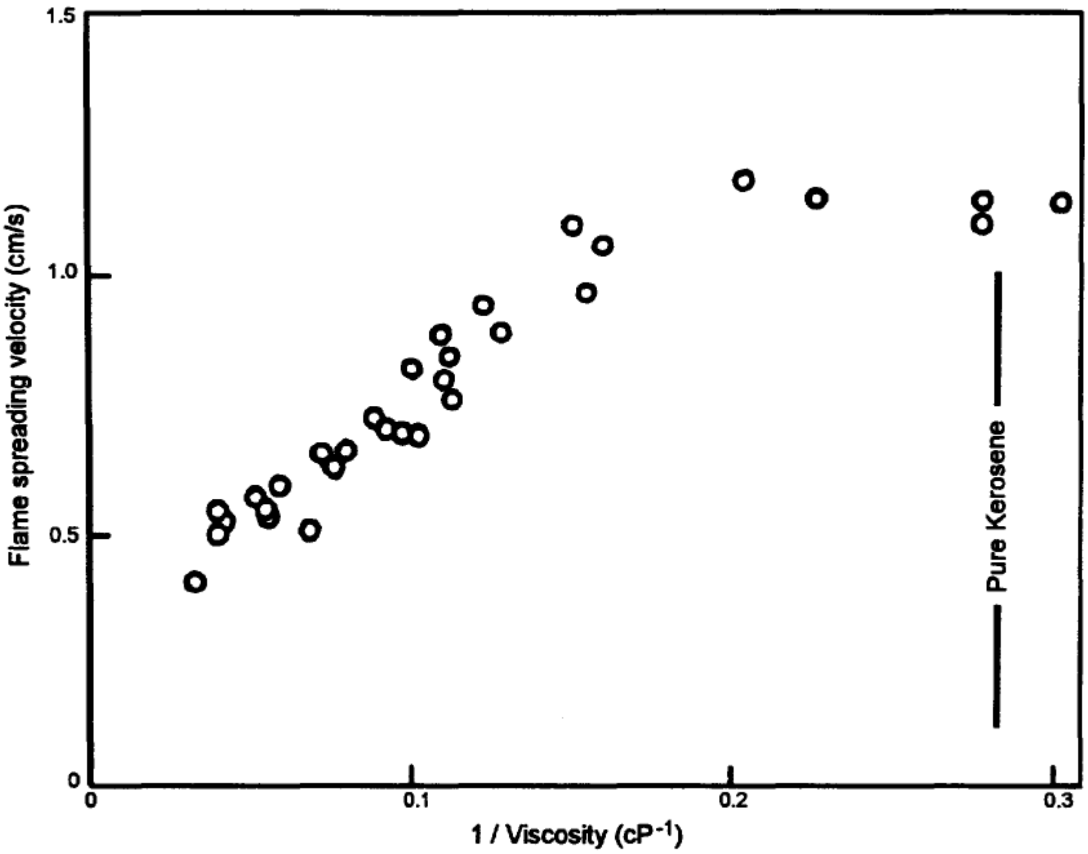

Figure 4 The flame spreading rate across thickened kerosene surfaces at room temperature (21°C) as a function of viscosity. A 3.5 mm kerosene film floated on 7.0 mm of water (from Glassman *et al*. 1969) (source: Marine Spill Response Corporation)

As the oil surface in front of the flame front heats up to the Flash Point, the flame flashes forward, consumes the vapour and flashes back. A few degrees warmer and the fuel temperature exceeds its Fire Point and continuous burning begins.

Many in-situ burning studies (e.g., Energetex 1977-1981, Evans *et al.* 1986, 1988, 1992, S.L. Ross 1989, SINTEF and S.L. Ross 1993) have measured flame spreading rates as the time for the flame to cover the entire surface of the slick and denoted this as ignition time. Their results indicate that, in quiescent conditions:

- as oil weathering increases, ignition time increases (i.e., the difference between ambient temperature and the oil's Flash Point increases, decreasing the flame spreading velocity);
- ignition times decrease with increasing slick thickness; and,
- for a constant thickness and Flash Point, increasing viscosity reduces flame spreading rates.

S.L. Ross and Energetex (1986) used a small wind tunnel to study flame spreading velocities and the effects of wind and ambient temperature. Their results for a fresh and weathered (unemulsified) crude and diesel fuel are shown on Figure 5.

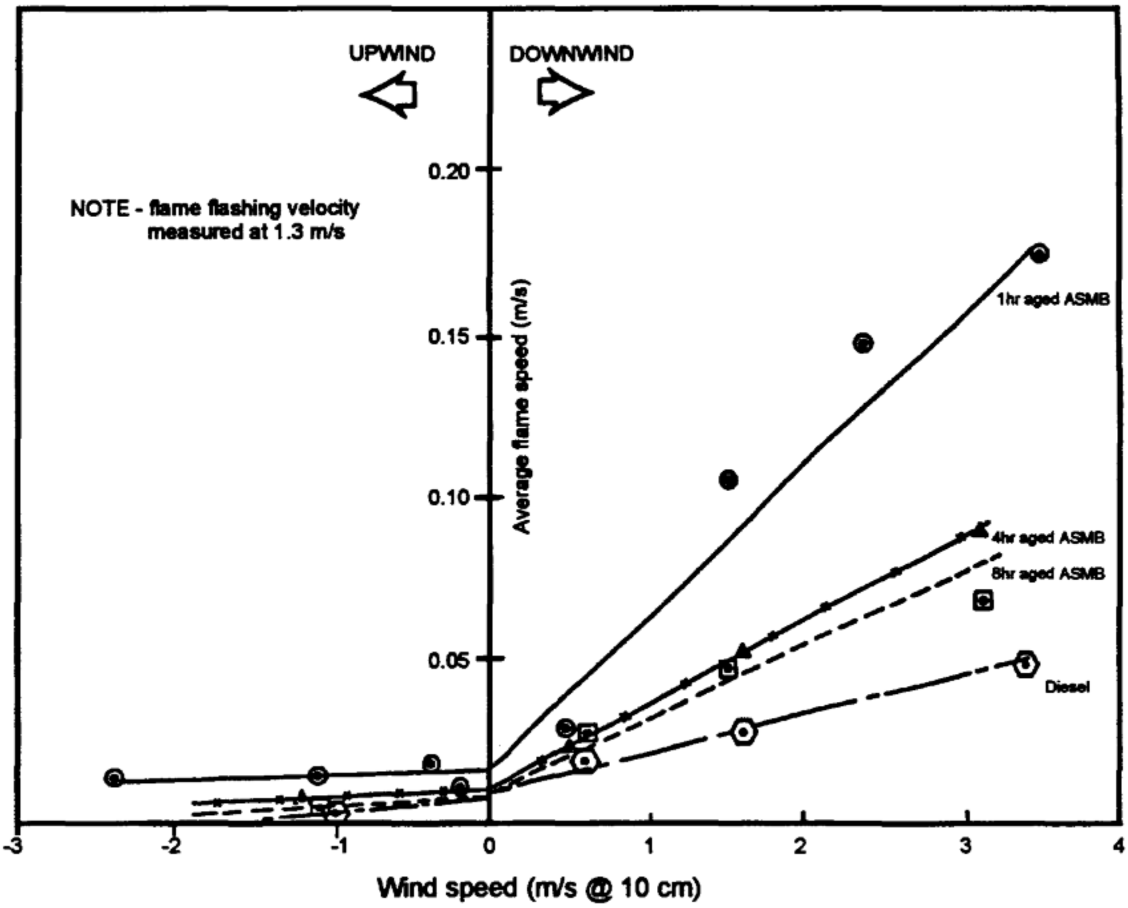

Figure 5 Flame spreading velocity (source: Marine Spill Response Corporation)

The data show that downwind spreading increases with increasing wind speed. This is due to bending of the flame by the wind enhancing radiative heat transfer to the slick (Energetex 1981). The flame velocity is also dependent on oil volatility.

The data in Figure 5 show that flame spreading upwind is slow but measurable. This spreading must be due to surface-tension-driven flow as radiative heat transfer on the upwind side of the flame would be very low. S.L. Ross and Energetex (1986) developed a simple model to reflect these effects on sub-flash flame spreading velocity. They based the oil volatility term on the initial boiling point of the crude rather than Flash Point, because Flash Point results vary greatly with the method and apparatus employed (Murty 1988). The model is:

- for upwind flame spreading

$$U_{F,U} = 1.3\exp(-7.88\,((T_B - T_A)/T_B)^{0.19}) \qquad (1)$$

where the term 1.3 is the flame flashing velocity in quiescent conditions

- for downwind flame spreading

$$U_{F,d} = U_{F,U} + u\ \exp(-6.52\,((T_B - T_A)/T_B)^{0.23}) \qquad (2)$$

Where

$U_{F,U}$; $U_{F,d}$ = upwind and downwind flame spreading velocities (m/s)
u = wind speed (m/s)

T_B = initial boiling point of the oil (as measured by ASTM D87 distillation) [°K]
T_A = temperature of oil slick [°K]

Data from Smith and Diaz (1987) indicate an upwind flame spreading velocity of 0.04 m/s for fresh Prudhoe Bay crude and 0.025 m/s for weathered crude against 4 to 7 m/s winds. For crosswind flame spreading the upwind flame velocity is used. This is consistent with the observation that, in windy conditions, flames spread nearly straight downwind from an ignition point without much crosswind spread (e.g., Energetex 1981, Dome 1981). If a slick has a large cross-wind dimension, it is necessary to ignite it at multiple points perpendicular to the wind across its upwind edge in order to achieve effective burning. Data reported in Bech *et al.* 1992 for downwind flame spreading velocities over slicks of weathered crude oil also show a trend in declining flame spreading velocity with increased weathering. Energetex (1981) concluded that flame spreading over emulsions is more sensitive to wind influences than unemulsified oils. Bech *et al.* (1993) and Guenette *et al.* (1994) gave the maximum wind speed for burning emulsions as 36 km/h (20 knots). SL Ross (1995) confirmed this.

It has been observed numerous times in the field that, although flame spreads slowly upwind or crosswind, the presence of a barrier or edge that provides a wind break can permit rapid upwind or cross-wind spreading.

Currents and regular waves (or swell) do not seem to affect flame spreading for unemulsified oils, but choppy or steep waves have been noted to curtail flame spreading (Energetex 1981, Dome Petroleum 1981a, Bech *et al*. 1993). Bech *et al.* (1993) have noted that flame spreading over emulsions is very sensitive to wave action; even regular, swell-type waves prevented ignition and flame spreading over heavily weathered, 25% water emulsions.

CHAPTER 2. IGNITERS

This section starts with a brief chronological history of the development of igniters. This is followed by a review of igniters that have been researched or developed but are no longer available. These discussions are followed by a more detailed presentation of commercially available igniter systems and some that are currently being considered for further test and evaluation.

2.1 Brief History of Igniter Development

Many different ignition devices have been used over the years to ignite or attempt to ignite marine oil spills. In 1967 four attempts were made to ignite seemingly thick oil slicks on the sea near the *Torrey Canyon* using pyrotechnic devices containing sodium chlorate, but these attempts were unsuccessful (Swift *et al.* 1968; Anonymous 1967). It was concluded that even though the spilled oil (Kuwait crude) had been on the water surface for only 40 minutes, it had emulsified to such an extent that it would not ignite.

Oil on the shore from the *Torrey Canyon* spill also proved virtually impossible to ignite and burn. Some success was reported in burning unemulsified oil in pools between rocks (Swift *et al.* 1968) using flame throwers to ignite pools. Emulsified oil could be burned on the beach as long as flame was applied directly to the oil. Once the flame was removed the combustion stopped.

Kontax was an igniter developed at the time by Edward Michels GmbH of Essen, Germany. It was demonstrated on a test spill off Holland where it successfully ignited and burned 10 tonnes of heavy Arabian crude (Freiberger and Byers 1971, Energetex 1978). The potential of Kontax was also demonstrated at the *Arrow* spill in 1970 where some of the spilled oil was primed with two drums of fresh oil and ignited with a Kontax igniter (Coupal 1972).

Another igniter - Oilex Fire, produced by Keltron Inc. of Switzerland - consisted of a sorbent (Oilex) plus a hydro-igniting agent. The company reported the chemical's use on small spills in Swiss lakes and in the Adriatic Sea (Freiberger and Byers 1971).

On December 27, 1976, the *Argo Merchant* went aground near Nantucket Island and spilled most of its cargo of 28,000 tonnes of No. 6 fuel oil. Part of the response by the U.S. Coast Guard involved attempts to burn the oil. One 30 m x 40 m x 15 cm thick slick was treated with Tullanox 500 (a wicking/insulating agent), primed with 200 L of JP-4 and ignited with JP-4-soaked cotton sheets set afire with a flare. About 95% of the Tullanox was blown off the treated slick by wind and the flames would not spread from the sheet to the primed slick. In another experiment, boxes of Tullanox 500 soaked with JP-4 fuel were dropped onto a slick from a helicopter and ignited with timed thermite grenades. The isolated boxes burned but the flames did not spread (Det norske Veritas 1979, Battelle 1979).

On January 28, 1977, some 300,000 L of No. 2 fuel oil was spilled onto ice-covered waters in Buzzards Bay, Massachusetts from the barge *Bouchard* #65. Boxes of Tullanox soaked with jet fuel were dropped from helicopters onto pools of oil in the broken ice with delay-fuses. Thermite grenades were used to ignite the boxes. The ensuing fires burned for 1-1/2 to 2 hours and consumed 4000 to 8000 L of oil. The 38 to 46 km/h (20 to 25 knot) winds drove the flames from pool to pool in areas nearby while in other areas the fires did not spread. Another series of burns was conducted at a later date, ignited with knotted rags soaked in diesel fuel (Schrier and Ediam 1979, Ruby *et al.* 1978).

Starting in 1977, considerable effort was devoted to developing an aerial ignition capability in support of potential spills from offshore exploration activities in the Beaufort Sea. Energetex

Engineering evaluated and tested five devices (Kontax, Kontax with gasoline, solid propellant, solid fuel, and gasoline with sodium). Solid fuel and solid propellant igniters with a fuse wire were ranked highest (Energetex 1978). Subsequently, two igniters were developed in Canada: the Dome igniter (Buist *et al.* 1981; Energetex 1982a and b) and the EPS igniter (Meikle 1981a and b, Twardawa and Couture 1983).

Laser-based ignition systems received considerable attention in the 1970s and 80s (Waterworth 1987, Whittaker 1987, Frish *et al.* 1989, Laisk 1976). A land-based system proved capable of igniting oil slicks on water and was demonstrated (Frish *et al.* 1989). The various components of a helicopter-borne system were researched under contract to Environment Canada and the Minerals Management Service (now the Bureau of Safety and Environmental Enforcement); however, further development of the prototype system awaits private sector involvement and possible commercialisation. High capital cost, energy requirements and platform stabilisation requirements to compensate for helicopter vibration and motion to permit steady focusing of the laser beam on targets (to preheat the oil) were believed to be a few of the reasons for not proceeding at the time.

In Alaska, a forest-fire fighting tool known as the Helitorch was discovered in the mid-1980s to be an effective aerial ignition system for oil spills (Allen 1986). Considerable testing and refinement of the device (Allen 1987) has resulted in the Helitorch being stockpiled around the world as the igniter-of-choice for in-situ burning.

Research efforts in the mid-1990s looked at extending the capabilities of ignition systems to deal with water-in-oil emulsions (S.L. Ross 1989, Bech *et al.* 1992, SINTEF and S.L. Ross 1993). In this work, emulsions with up to 40% water content were successfully burned, however, higher-strength igniters using gelled crude oil, rather than the conventional use of gelled gasoline, were required for successful ignition. Further work by Guenette and Sveum (1995) used various gelled fuels (gasoline, diesel, and Bunker C), an emulsion breaker and an anti-foaming agent to successfully ignite and burn emulsions with water contents of up to 50%. The work showed the potential for the concept of a one-step break-and-burn process for igniting and burning emulsions. During trials off Lowestoft, England in 1996 (Guenette and Thornborough 1997), the concept was demonstrated using a Helitorch to deliver the emulsion breaker and fuel mixture to successfully ignite and burn emulsions.

There has been little work done on aerial igniter development in the last two decades. The Heli-torch is still stockpiled by some response organisations, and has been used in field trials such as the NOBE experiment in 1993 (Fingas *et al.* 1994), the Lowestoft trials in 1996 (Thornborough 1997), two inland burns in Utah (Williams et al. 2003), and recent tests of aerial application of herders near Fairbanks, Alaska (Potter *et al.* 2015). Other field trials and operational uses of in-situ burning have used simple ad-hoc igniters. For example, during the response to the Macondo blowout in 2010, in-situ burns were initiated using igniters assembled from off-the-shelf components: a marine signal flare attached to a plastic bottle filled with gelled fuel (Mabile 2010). The Heli-torch was not employed at the Macondo blowout because of the distance of the ISB operations from shore.

Inland or marsh burns are commonly initiated using propane weed burners (May and Wolfe 1997, Hess et al. 1997).

The US Navy Supervisor of Salvage (SUPSALV) undertook a programme to develop an igniter that did not require a helicopter to deploy and that could be shipped safely by surface or air transport (Moffatt and Hankins 1997). Through an iterative process involving experimentation with different fuel compounds, a flare-type device was produced that could successfully ignite and burn diesel fuel and 25% water content emulsions. This unit was never commercialised.

Recently, Elastec and Desmi-AFTI have developed commercially available handheld ignition system based on the technology used for ad-hoc igniters in the *Deepwater Horizon* response.

2.2 Summary of Disused Ignition Systems

The following ignition systems had been used or were researched at one time but are no longer available, recommended, or considered for use:

2.2.1 Kontax

The Kontax igniter was produced by Edward Michels GmbH of Essen, Germany. Production of the device ceased in the mid-to late-1970s (Energetex 1978). The device consisted of a 4 cm diameter cylindrical metal screen 30.5 cm long and capped at both ends. A metal bar coated with metallic sodium ran through the centre of the cylinder. The annulus was filled with calcium carbide. The device weighed 1.2 kg. For safety reasons the Kontax igniter was stored in a sealed plastic bag.

The Kontax igniter had a unique feature: it did not require activation or a starter. When the device was exposed to water the sodium metal reacted to produce heat and hydrogen, which instantly ignited. At the same time the calcium carbide reacted with water to produce acetylene which was subsequently ignited by the burning hydrogen. The flame from the burning acetylene preheated and ignited oil vapours.

Tests to evaluate Kontax were conducted in 1969 by the Dutch government (Battelle 1979). The tests were conducted 25 miles offshore and on beaches; the oils used were heavy and light Arabian crude. One test involved a 9 tonne slick covering about 2000 m^2 (0.5 cm thick) in a free-floating lumber boom. The bags containing the Kontax were punctured and thrown into the slick. The igniters were successful; flames of 15 to 20 m high were reported and 98 to 99% oil removal efficiency was estimated. A Kontax-to-oil ratio of 1: 100 by weight was judged to be appropriate.

Tests with the Kontax igniter (Energetex 1978) showed that it produced a large flame area (3000 cm^2) with a relatively low flame temperature (770° C). This combination produced a relatively high flame emissivity of 2.25 kW/m^2. Although Kontax proved effective in both field and tank trials as a surface-deployed igniter (Freiberger and Byers 1971, Energetex 1978), the device proved less effective when dropped from a height of 11.5 m, simulating deployment from a helicopter. The ignition success rate declined from 100% in the surface tests to 60% in the aerial tests. The main reason for the latter result was that the large splash caused by the Kontax igniter entering the water drove the oil away; by the time the oil had returned, the igniter had generated a ring of calcium hydroxide foam that kept the oil away.

Energetex (1978) tested a modification to the Kontax igniter, which involved combining a small amount of gasoline with the device. This inclusion of gasoline was intended as a fuel to bridge the calcium hydroxide foam barrier. This modification resulted in a slightly higher flame temperature (790° C) and better aerial deployment ignition success (80%).

It is not clear why Kontax was taken out of production. It may have been due to a general lack of interest in in-situ burning at the time, or due to the potential dangers and stringent requirements for storing, transporting, and using the igniters.

2.2.2 *Solid Propellants*

Solid propellants, also known as solid rocket fuel, are composed of a solid mixture of various portions of ammonium perchlorate oxidiser, metal fuel (magnesium or aluminum), and an organic binder. They have been used in a variety of igniters. Solid propellant igniters, in various shapes and utilizing various starters (electrical, chemical or fuses) have been extensively tested (Energetex 1978). Such igniters exhibit very high flame temperatures (about 1230°C) and high flame emissivities (1.75 kW/m^2) but are consumed rapidly. They require mounting in a housing to suspend them no more than 5 cm above the oil/air interface. In water surface tests, solid propellant gave an 89% ignition success rate; and an 80% success rate in aerial-deployment tests with a fuse-wire starter (all other starter mechanisms resulted in lower success rates).

Solid propellants were once considered but now are not recommended for use alone as an oil spill igniter. Rather, they and solid fuels (discussed next) are used in conjunction with other components in currently available igniter systems.

Examples of igniters that were developed using solid propellant include the Dome igniter (still stockpiled by ACS in Alaska) and the EPS Igniter.

2.2.2.1 *EPS Igniter*

The Environmental Protection Service (EPS) Igniter was an air-deployable pyrotechnic device developed by the Canadian Environmental Protection Service, a division of Environment Canada, in cooperation with Canadian Department of National Defence Research Establishment, Valcartier (DREV) and the Arctic Marine Oilspill Program (AMOP) (Twardawa and Couture 1983). The igniter (Figure 6) is approximately 25 cm square and 13 cm high and weighs nearly 2 kg. The unit consists of a pyrotechnic device sandwiched between two layers of foam flotation and is activated by a self-contained firing mechanism. It is intended to be a hand-thrown device.

The EPS igniter was marketed in the past as the "PYROID" igniter manufactured by ABA Chemical Ltd., but the company is no longer in business. Although the device is not commercially available, the design is available from Environment Canada's Emergency Engineering Division.

The device is simple in design and operation, being activated by pulling on a firing clip which in turn strikes a primer cap. A 25-second delay column then provides sufficient time to throw the igniter and let it settle within the target oil slick. A specially formulated ring of fast-burning ignition composition is then ignited, and this in turn ignites the primary incendiary composition. The incendiary composition is a solid propellant consisting of typically 40 to 70% ammonium perchlorate, 10 to 30% metal fuel (magnesium or aluminum), 14 to 22% binder, and small amounts of other ingredients to aid in the casting and curing processes. These materials have an estimated shelf life of about 5 years.

The firing mechanism and the incendiary materials are sandwiched between two polystyrene foam slabs to provide both buoyancy and protection for the device on impact. All components except the firing mechanism are combustible, so that very little debris is left in the environment after a burn. These components have also been designed so that the igniter experiences a minimum of roll if dropped onto a hard surface (like ice) or shallow water. The igniter can float in as little as 5 cm of water/oil. The flame it produces will be oriented properly regardless of which side of the igniter is up. The EPS igniter has been designed to produce a ring of fire with temperatures approaching 2,000°C immediately adjacent to the perimeter of the igniter. This intense flame has a typical duration of about 2 minutes.

The EPS igniter has been designed so that no open flames or sparks are experienced aboard the deployment helicopter. Once the igniter is activated, however, there is no way to deactivate the igniter -it must be thrown from the helicopter within the 25-second delay period. Prior to activation, there is very little chance of an accidental firing because there is a safety pin in the firing mechanism.

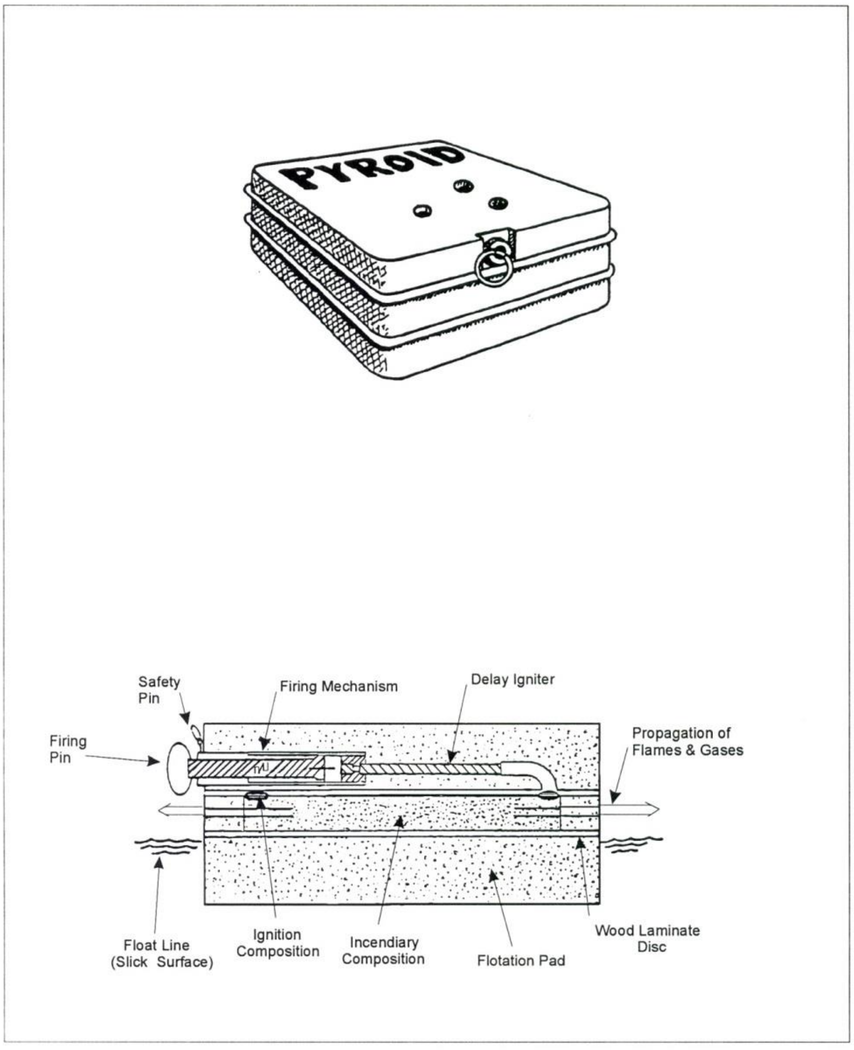

Figure 6 Environmental Protection Service (EPS) igniter, or Pyroid igniter, showing internal firing mechanism and pyrotechnic components (adapted from Allen 1986) (source: Marine Spill Response Corporation)

The EPS igniter was designed to provide a 75% probability of functioning properly when dropped at an airspeed of about 30 km/h from an altitude of approximately 15 m. Actual field tests indicate that a high probability of success can be achieved with newly constructed devices but as the 5-year shelf life is approached, the probability of functioning properly begins to drop off. It is therefore important that stockpiled igniters be carefully dated and then reconstructed as their shelf lives expire. The cost of tearing down and replacing the pyrotechnic portion of the igniter is estimated to be about 25% of the original manufacturing price. The plans for the EPS igniter may be obtained from:

Emergencies Engineering Division
Environment Canada, Conservation and Protection
River Road Environmental Technology Center
3439 River Road Ottawa, Ontario, Canada, KIA OH3
Fax: (613) 991-1673

2.2.2.2 *ESSM Flare-type Igniter*

The ESSM Flare-type Igniter IG0010 (Table 2) is a pyrotechnic device consisting of a mixture of metals, chemicals, and organic binders that ignite by a small amount of energetic compound. An electrical filament connected to the flare ignites this energetic compound which, in turn, lights the metal/binder mixture. The result is a very hot flame that heats and ignites the oil slick. Engaging the safety jumper and power switch activates the igniter. After a timed 2.5- to 5-minute delay, the flare is energised and ignited. The delay allows time for the igniter to drift into the oil slick, and for the deployment personnel to distance themselves from the burn area. The igniter was redesigned so that the igniter can be removed from the flare material. This two-piece configuration allows it to be shipped by air.

Table 2. ESSM Flair-type Igniter Dimensions

Length	**Width**	**Height**	**Volume**	**Weight**
16 in	4 in	4 in	1 ft^3	4 lb

Cartridge Actuated Devices, Inc.
51 Dwight Place
Fairfield, NJ 07004
Tel: 973-575-1312
Web: www.cartactdev.com

2.2.3 *Solid Fuel*

Solid fuel igniters employ gelled kerosene cubes (e.g., solid barbecue starter) suspended above the oil/air interface. Because of the lower flame temperatures (770° C) and flame emissivities (0.5 kW/m^2) generated, it is necessary to suspend the cubes within 3 cm of the oil surface in order to successfully ignite oil. Surface ignition tests have resulted in an 84% success rate while aerial tests resulted in an 80% success rate using a fuse wire starter (Energetex 1978). Solid fuel is used in one presently available oil slick igniter discussed in the following section.

2.2.4 *Thermite*

Thermite is a mixture of metallic aluminum powder and ferric oxide. Although producing extremely high temperatures (about 3500° C) the mixture requires a very high ignition temperature (about 2000° C) which necessitates specialised starters. Military incendiary devices utilise thermite.

Although thermite has been used with some success at several spills, as noted earlier, it is no longer recommended as an oil spill igniter due to its stringent storage and transport requirements.

2.2.5 Marker Flares

A number of types of marker flares have been considered or used as oil slick igniters. These include both road and marine flares of the phosphorous, calcium hydroxide, and magnesium types. They can be successful in igniting fuels at temperatures above the fuel's Flash Point or in igniting a primer liquid placed on a sub-flash fuel (Freiberger and Byers 1971). They are not effective in directly igniting sub-flash oils (Energetex 1978). Marine flares are incorporated into several hand-held igniter designs that are presently available (AFTI Hand-held, Safe Start and the Simplex Model 901) and were used as an ad-hoc igniter in recent tests of a UAV helicopter as a platform for spraying herder and igniting the herded slick (Potter et al. 2015). In this latter use, the flare is ignited remotely using an “electronic match” initiated via a radio signal.

2.2.6 Proprietary Ignition Chemicals

Two proprietary ignition systems have been reported in the literature (Cabioc'h 1993). These are Westcom 2000 and Westcom 2001 (also known as Westcom II and III respectively). Westcom 2000 is a coarse granular mixture incorporating a hydro-igniting chemical and oxygen donation catalyst. It is contained in a sealed plastic bag that must be cut before being thrown onto the slick.

Westcom 2001 is a viscous colorless gel intended to be sprayed on the surface of an emulsified slick to ignite it and promote its combustion, with initial ignition provided by Westcom 2000. Experience with the product indicates that it offers only a small advantage over gelled diesel fuel and the on-site mixing and spraying is cumbersome. Furthermore, it has been noted that the use of Westcom 2001 reduces the capacity of sorbent pads on the residue that remains after a burn (Cabioc'h 1993). Although the product has been tested successfully in both temperate and Arctic climates, the current view is that it should not be considered for use, primarily because of safety concerns regarding the storage and handling of such hydro-igniting chemicals on vessels or aircraft.

2.2.7 Hypergols

Hypergols consist of two liquids stored separately; one is a strong oxidant (such as fuming nitric acid) and the other is combustible. When mixed, they burn rapidly, particularly when the oxidant provides its own oxygen. These have been considered for use as oil spill igniters, but are currently rejected because of the hazards in storing and mixing the reagents (Energetex 1978).

2.2.8 Sodium and Gasoline

Tests were carried out on an igniter consisting of a small plastic bag filled with gasoline connected to a wire enclosure containing a piece of metallic sodium (Energetex 1978). The device was unsuccessful during surface tests because the sodium failed to ignite the gasoline. This occurred for two reasons: sodium coated with gasoline or oil does not react vigorously enough with water; and the sodium tended to escape from its container. Storage and handling problems would also be anticipated with this type of device. Tests conducted in 2004 with a slurry of metallic sodium and kerosene produced similar results (SL Ross 2004).

The use of a sodium-silicon compound (NaSi) was examined by Buist (2005). Granules of sodium silicide were able to ignite slicks of fresh crude oil thicker than about 1 mm; however, the slicks extinguished before the oil (and the NaSi) was completely consumed. The NaSi granules remaining in the slick after extinction could pose concerns for residue recovery operations. Although the NaSi granules could ignite fresh crude, the short duration of the flames generated by the NaSi reacting with water, about 10 seconds, compared with several minutes for conventional ignition systems ranging from 2 minutes to 10 minutes burn time, raised questions about the ability of NaSi granules to ignite weathered oil slicks that need to be pre-heated to their Flash/Fire Point before ignition will take place.

2.2.9 Premo Aerial Ignition Device (AID)

The Premo AID (also known as the Plastic Sphere Dispenser – PSD) is a system designed for the ignition of debris and backfires in forest fire control. The ignition component of the system consists of 3 cm diameter polystyrene spheres each containing approximately 3 grams of potassium permanganate. The igniter is started by injecting the cylinder with 1 mL of glycol. A highly exothermic reaction is initiated which results in combustion of the device and its contents for a period of 20 to 30 seconds. Flame size and ignition delay are varied by changing the grain size and mass of potassium permanganate, and by diluting the glycol with water.

The delivery component of the AID system consists of a mechanical dispenser comprising a storage hopper, injection chambers and exit chutes. The polystyrene balls are mechanically fed into the injection chambers, injected with glycol and then immediately ejected into the exit chute. The dispenser also contains a water reservoir and fire extinguishing system should a ball jam after injection. The dispenser is designed to be strapped to the floor of a helicopter, extending out the open rear door. The device is equipped with tie down straps and a break-away electrical connection so it can be quickly jettisoned in an emergency.

In recent years newer designs for both the helicopter-mounted launcher, the container for the potassium permanganate and the chemical to inject and start the exothermic reaction have been developed:

- http://www.fs.fed.us/t-d/aerial_ign/plsphere/describe.htm
- http://www.raindancesystems.com.au/under-development/

When this device was tested for use as an oil spill igniter (Spiltec 1987), it was found that the igniter was easily doused and it sank when water was splashed on the burning ball. Potassium permanganate is soluble in water. A recent review of igniters for inland ISB (API 2015) stated that, for the plastic sphere dispenser system: “Use on water is not usually successful because the components are water soluble.”

2.3 Presently Available Ignition Systems

There are several ignition systems that have proved to be effective and are either commercially available or can be constructed from technical designs if needed. The discussion of these is divided into two sections: igniters for use from a vessel or land vehicle, and igniters for use from helicopters.

2.3.1 Surface-deployed Igniters

Both portable propane or butane torches, or weed burners, and rags or sorbent pads soaked in diesel have been used successfully many times in the past to ignite oil slicks on water. Experience has shown that propane torches tend to blow thin oil slicks away from the flames and are best utilised on thick, contained slicks. Diesel is preferred over gasoline as a fuel to soak sorbents or rags for use as igniters as it results in a more powerful flame (Buist *et al.* 1983d). A variation on this sorbent igniter was used at OHMSETT in the 1980s (Dome 1981a, Smith and Diaz 1987). It involved sorbent wrapped around a short length of Ethafoam log, dipped in diesel or crude oil, and then sprayed with dimethyl ether (also known as starter fluid). This ignited easily and burned for a long time, even in choppy wave action.

Another successful surface-based igniter is gelled gasoline. Allen (1990a or b) reports that the in-situ test burn during the *Exxon Valdez* spill was ignited using a plastic bag containing gasoline gelled with "Surefire" gelling agent. The contents of the bag were mixed by hand, placed on the water surface then ignited and allowed to drift from the tow boat into the contained oil in the fire containment boom being towed behind. The manufacturer of the Helitorch (see below) also offers a land-based version called the Groundtorch (Spiltec 1987). Other forest fire fighting suppliers offer similar systems with a range of sizes and capacities designed for mounting on a number of land vehicles. These devices consist of a storage drum and pump connected to a hand-held or vehicle-mounted "wand" for application of the burning gelled gasoline. These systems are variously designed for mobile use with a pickup truck, small trailer or ATV.

The most commonly used igniter in recent experiments and in-situ burn operations, including in the Macondo response, has been the use of gelled petroleum fuel in combination with a marine distress flare (Mabile 2010). The igniter can easily be assembled on-scene using off-the-shelf components. A flare is attached to a plastic container filled with gelled fuel and taped to floats that are consumed in the fire. When activated, the flare burns through the wall of the container, releasing its contents. The burning fuel then spreads out, pre-heating the surrounding oil, and igniting the contained slick.

Variations on the gelled fuel have been reported by Bech *et al.* 1992, who mixed “Surefire” gelling agent with gasoline, diesel, and fresh crude oil. The flame temperatures measured by an infrared video system increased from gasoline to diesel to fresh crude. Further experimentation with other chemical additives such as ferrocene (for smoke reduction), anti-foaming agents and emulsion breakers has indicated that further improvements with gelled petroleum igniters may be possible (SINTEF and S.L. Ross 1993, Guenette and Thornborough 1997).

In a 2006 study of fuels that could be used with commercial gelling agents to produce gelled fuel for forest fire fighting purposes, the Forest Engineering Research Institute of Canada identified that diesel and ethanol blended gasolines did not perform well with the traditional gelling agent Petrol Jel (http://wildfire.fpinnovations.ca/43/PetroJelReport.pdf). At present almost all gasolines are blended with ethanol. The effect of this on gelling success with a variety of gelling agents should be explored.

2.3.1.1 *AFTI Igniter*

As a result of their experience during the *Deepwater Horizon* in-situ burning operations, Desmi has developed a simple hand-held igniter kit (Figure 7) that consists of a cardboard box containing two empty plastic gallon jugs, polyethylene foam packing, a ballast weight and a receptacle for a marine flare. The flare and fuel to be gelled (diesel or gasoline) are to be supplied by the customer. The gelling agent can be supplied either by Desmi or the customer.

The AFTI Igniter is produced and marketed by:

Desmi, Inc. (formerly Applied Fabric Technologies, Inc.)
1119 Cavalier Blvd.
Chesapeake, VA 23323, USA
Phone: (757) 857 7041
Fax: (757) 857 6989
E-mail: desmi@desmi.com

Figure 7 AFTI Hand-held Igniter (source: DESMI)

2.3.1.2 *Safe Start Igniter*

The Elastec/American Marine Safe Start Igniter (Figure 8) is designed to provide a safe and easy way to start controlled burns. Each 1 gallon (3.8 L) container is preloaded with non-toxic Safe Start gelling agent to be mixed with diesel fuel. A common marine flare, when ignited, will melt the container, allowing the gelled burning fuel to spread to an approximately 1-metre diameter fire that lasts up to 5 minutes.

Figure 8 Safe Start hand-held igniter. (source: Elastec / American Marine)

The Safe Start Igniter is produced and marketed by:

Elastec American Marine, Inc.
1309 West Main
Carmi, IL
USA 62821
USA
Tel: 618-382-2525
Fax: 618-384-2740
E-mail: elastec@elastec.com

2.3.1.3 *Simplex Model 901 Hand-held*

This igniter was used successfully in an experimental burn in 1996 in England. It consists of a 1-quart polyethylene bottle filled with gelled gasoline. The bottle is fitted with two foam floatation collars (Figure 9, Table 3), and a marine hand-held distress flare is attached to the outside of the bottle to provide the ignition source. The flare should be positioned such that it extends 1.5 inches beyond the bottle: this allows the user to hold the igniter for 10 to 20 seconds and ensure that it is burning properly before deploying it. The flare is ignited and the device is thrown in front of the slick and allowed to drift into it. The flare burns for approximately 1 minute before it burns through the plastic bottle and ignites the gelled gasoline as it is released from the bottle. The 1-minute delay allows time for the igniter to drift into the oil slick and for the deployment personnel to distance themselves from the burn area.

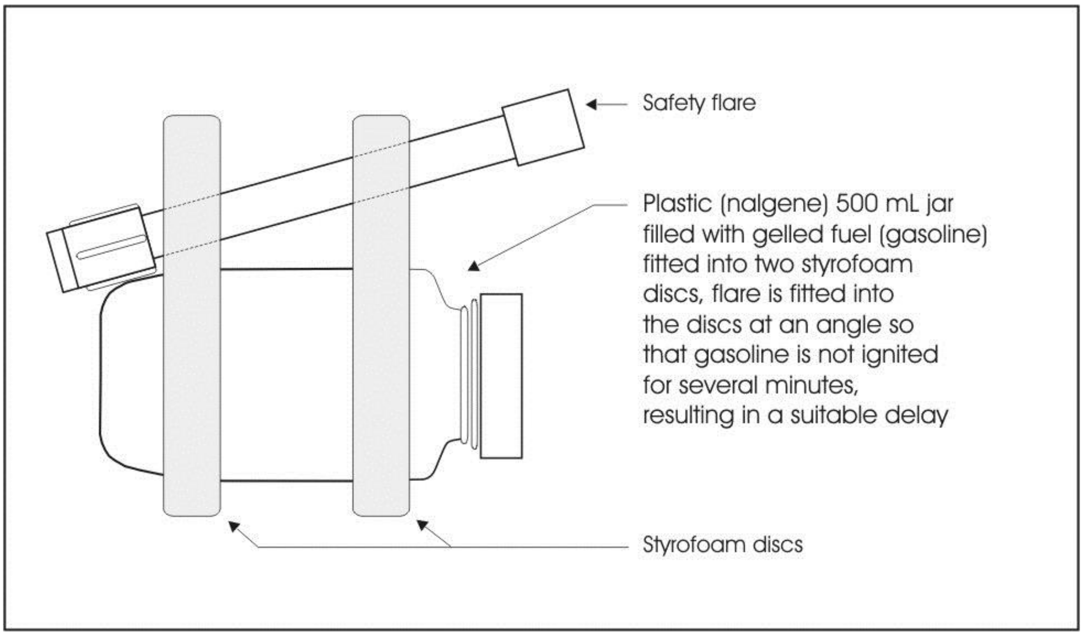

Figure 9 Simplex Hand-held Flare Igniter (Fingas and Punt, 2001)

This device is available from Simplex (contact information below). Alternatively, an ad-hoc version of this relatively simple device could be made at the time of a spill with readily available materials.

Table 3. Simplex Hand-held Igniter Model 901 Dimensions

Length	Width	Height	Volume	Weight
8 in.	8 in.	4 in.	2 ft^3 for 12 igniters	Shipping: 5 lb per 12 igniters Use: 1.5 lb per igniter when full of gelled fuel
Dimensions estimated				

Simplex Manufacturing Co. dba Simplex Aerospace
13340 NE Whitaker Way
Portland, OR 97230
UNITED STATES
Phone: +1 503-257-3511
E-mail: mail@simplexmfg.com
Web: www.simplexmfg.com

2.4 Aerially-deployed Igniters

There are two aerially-deployed igniter systems that are currently available for use on oil spills, as discussed in the following section (adapted, with permission, from Allen 1986).

2.4.1 Dome Igniter

The Dome Igniter (also known as the Energetex Igniter) is a lightweight air-deployable pyrotechnic device developed by Dome Petroleum Ltd., Calgary, Canada, in cooperation with Energetex Engineering, Waterloo, Canada. The igniter (Figure 10) measures approximately 30 cm by 18 cm by 11 cm and weights a little over 0.4 kg. The unit consists of a wire-mesh fuel basket with solid propellant and gelled kerosene slabs suspended between two metal floats. Like the EPS igniter, the Dome unit is intended as a hand-thrown device.

The Dome Igniter was manufactured by Energetex Engineering and came to be known as the Energetex igniter or the “tin-can” igniter. It went through several design changes since it was first tested by Dome during the winter of 1979/80 (Buist *et al.* 1981). These changes involved the igniter's mode of activation and the way in which certain components in its fuel basket are isolated from each other (Energetex 1982b). In order to avoid any need for open flame during activation, the fuse wire is started with a specially designed electric ignition system referred to as the Energetex Engineering Ignition System (EEIS). Consisting of a 12-volt spill-proof battery with a gel electrolyte and a heater element, the EEIS can provide sufficient heat to activate the igniter's fuse wire within two seconds of contact. Once started, the 25 cm long safety fuse provides about 45 seconds of delay for throwing the igniter and allowing it to settle within the target oil slick.

Although the Dome igniter is not in common use, it is still held in inventory by some response organisations and is included in this summary on that basis.

The fuse ignites a thermal igniter wire, which in tum ignites the solid propellant slabs located above and below the igniter wire. The solid propellant burns intensely for about 10 seconds with temperatures in excess of 1200°C. During this initial burn, the gelled kerosene begins to burn, producing temperatures of 700°C to 800° C. The total burn time for the igniter is about 10 minutes.

The device is designed so that the fuel basket housing the propellant and gelled kerosene is suspended above the oil layer. Oil between the floats and beneath the fuel basket is somewhat shielded from the wind to allow heating of the oil. The relatively long burn-time for the Dome igniter helps ignite the slick if winds temporarily separate the igniter from the heaviest concentrations of oil. Upon completion of the burn, all of the metal components of the igniter remain on the surface of the water and attached to the two floats.

The low weight and irregular shape of the igniter give the igniter a relatively low terminal velocity and a tendency to avoid rolling on impact with solid surfaces. The igniter has only two stable positions in which it can float and either one keeps the igniter's flames in close proximity to and slightly above the oil.

The fuse wire of the Dome igniter must be kept away from any potential sources of ignition. Once activated, the igniter cannot be deactivated, and it must be released as soon as possible (at least 20 to 30 seconds before the end of the 45-second delay period). Proper packaging in separate plastic bags and storage of the units in cardboard boxes onboard the helicopter should be sufficient to prevent any accidental activation of an igniter.

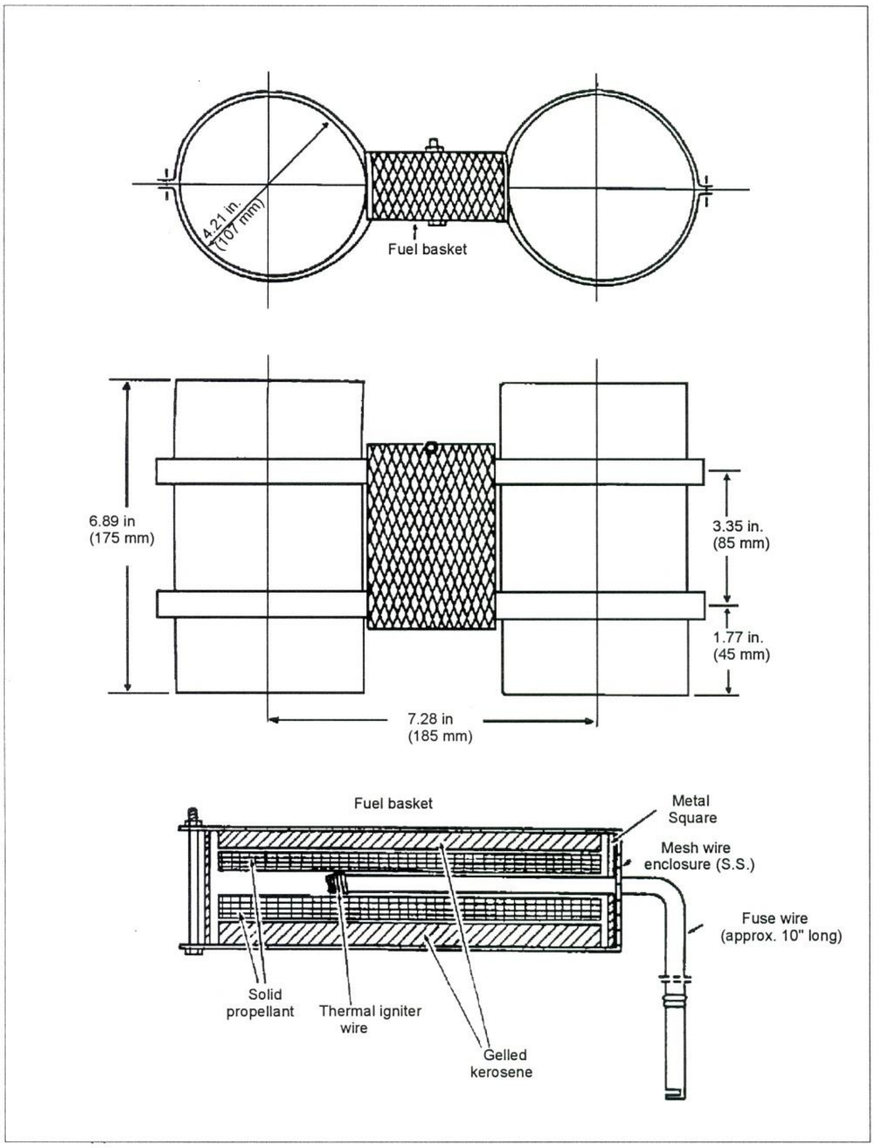

Figure 10 Basic design and internal components of the Dome or Energetex igniter (adapted from Allen 1986) (source: Marine Spill Response Corporation)

Based on the Dome igniter's explosives classification, it need only be stored in a spark-free, dry area and be packaged and properly marked as a pyrotechnic firework. The igniters should be stored in a secure place, safely removed from any heat sources and other flammable materials. The Dome igniter has undergone rigorous testing (Energetex 1982b) over a broad range of temperatures (-70°C to 50°C) and vibration and humidity conditions normally used for such explosives manufactured and used in Canada.

The simplicity of design of the Dome igniter provides a good probability of success. Its starter fuse and ignition wire have at least 95% reliability, and experience both in the U.S. and Canada suggests that the probability of activating the entire contents of the fuel basket is in excess of 90%. As with any pyrotechnic device, the probability of success is expected to diminish as the shelf life of each unit is approached.

The igniter has been extensively tested and shown to be capable of igniting fresh, weathered and emulsified oils (up to 60% water) in temperatures as low as -30°C and in winds up to 40 km/h (Dome 1981b, Energetex 1978, 1979, 1981a, 1982b).

The shelf life of the Dome igniter is estimated at about five years, although experience with igniters stored in Alaska and Canada has shown that they will operate after 15 to 25 years (Allen 1992, SL Ross *et al.* 2003). It is important that any stockpiled igniters be carefully dated, periodically tested and reconstructed as necessary. Tearing down and replacing the pyrotechnic portion of the igniter will cost approximately 50% of the original purchase price.

The current manufacturer of the Dome igniter is:

Energetex Engineering
505-125 Lincoln Road
Waterloo, Ontario, Canada, N2J 2N9
Fax: 519-885-2738

2.4.2 Heli-Torch (adapted with permission from Allen 1987)

The Heli-torch (Figure 11) is a proven aerial ignition system commonly used by the U.S. Forest Service and the Canadian Forestry Service for burning forest slash and for setting backfires during fire-control operations. It is a completely self-contained unit consisting of a fuel barrel, pump, and motor assembly slung beneath a helicopter and controlled with an electrical connection from the Heli-torch to a panel in the cockpit. The fuel barrel can be filled with a gelled gasoline or gasoline and diesel mix which is then pumped on demand to a positive-control shut-off valve and ignition tip. The gelled fuel mixture is ignited with electrically-fired propane jets as it exits one or more nozzles protected by wind shields. The burning gelled fuel falls as a highly viscous stream and quickly breaks up into individual globules before hitting the ground. Three models are available with 110 L, 205 L and 1100 L (30, 55 and 300 gal) capacities. Of these, the 205 L (55 gallon) model has been most extensively tested for use on oil spills.

In fighting forest fires, the Heli-torch may be operated from heights of several hundred feet and with speeds of 40 to 60 mph (65 to 95 km/h). Such heights and airspeeds are not desirable for the ignition of oil slicks at sea. Depending upon the actual nature of the slicks to be ignited, flying at much lower altitudes (8 to 23 metres) and with airspeeds of 40 to 50 km/h may considerably enhance the accuracy, ignition success and distribution of burning globules.

The Heli-torch ignition system is manufactured by Simplex Aerospace Co. in Portland, Oregon (www.simplexmfg.com), and is approved by the U.S. Federal Aviation Administration (FAR Part 137). U.S. users of the system are cautioned that certain federal regulations (46 CPR) require approval by the Office of Hazardous Materials Transportation (OHMT), U.S. Department of Transportation, for transporting fuel beneath a helicopter (e.g., sling-loaded Heli-torch) and for transporting the fuel to support a gelling operation at a remote site. Exemptions from these requirements have been obtained for such operations as forest fire control; nevertheless, application for exemption involving oil spill control must be requested.

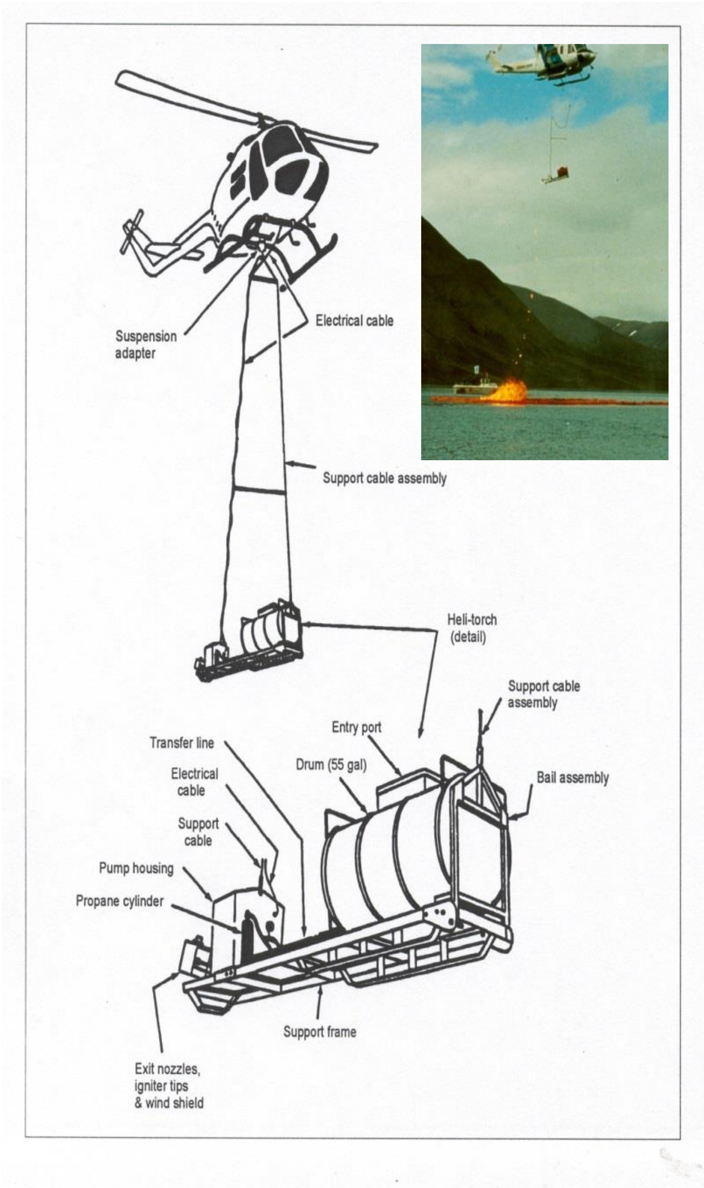

Figure 11 Heli-Torch Components and Support System (adapted from Allen 1986) (source: Marine Spill Response Corporation; photo: A. Allen)

The gelling mix used to thicken the gasoline (or diesel as the case may be) often involved SUREFIRE, a gelling agent available from Simplex (Portland, Oregon) and from Fire-Trol Holdings, L.L.C. (the exclusive U.S.A. distributor for FIRE-TROL Fuel Gelling Agent, previously sold as SUREFIRE®).

The Heli-torch can be carried by a helicopter with a cargo hook and a 24-to 28-volt power supply. When the single-point suspension cable system is used with helicopters employing swivel cargo hooks (e.g., Bell 250, 212, 412), the Heli-torch may experience temporary rotation. However its design normally allows the unit to achieve a stable orientation and fly without any loss of its globule-ignition or distribution characteristics.

Depending upon the helicopter used (i.e., with fixed or swivel cargo hook), the Helitorch support assembly may be rigged to include a self-releasing horizontal support arm or stabilizing bar to keep the Heli-torch oriented properly. The stabilizing bar can be suspended at one end directly below the cargo hook, with the other end of the bar resting on one of the helicopter's skids. The Heli-torch's support cable assembly is then connected directly to the stabilizing bar. This approach provides a stable two-point connection while permitting the Heli-torch to be jettisoned if necessary. Both support systems (i.e., with and without the stabilizing bar) were used during field trials (Allen 1987).

The weight of the Heli-torch with a full 205 L (55 gallon) drum is approximately 243 kg (534 pounds). The entire unit is connected to a helicopter with a support cable assembly that can be jettisoned quickly from the helicopter's cargo hook. The electrical cable has a quick-disconnect plug near the helicopter, and this plug can also be pulled apart easily if the unit is released in an emergency.

SUREFIRE[1] is a fine powder that when mixed with liquid fuel produces a smooth, viscous gel. When typical ratios of 1.8 to 2.8 kg (4 to 6 pounds) of SUREFIRE to 205 L (55 gallons) of fuel are used, adequate viscosities for Heli-torch use can normally be achieved within a matter of minutes at room temperature. At sub-freezing temperatures, ratios of 5 kg (11 pounds) to 205 L (55 gallons) are required for gelling to occur in 30 to 40 minutes. The gelling mix is poured through the entry port of the Heli-torch fuel storage drum, which is equipped with a hand crank for mixing. Separate, portable gelled fuel mixing tanks are available from the manufacturer.

The Heli-torch is operated with a positive-displacement pump producing a flow of approximately 55 L/min. When operated with a 205 L holding drum, the Heli-torch can provide a total application time of about 3 minutes and 40 seconds. The drum would then have to be refilled with gelled fuel or replaced with another drum already filled. The 205 L Heli-torch model is rigged so that an empty drum can be removed from the support frame and replaced with a full drum quickly and safely.

Burning gelled gasoline globules released from heights of a few m to 18 m continue burning after impact. Even without oil on the water's surface, splash effects are tolerable, and elongated “pancakes” of gelled burning fuel result with sizes (if expressed as a circle) typically 13 to 18 cm in diameter.

Experience suggests that the average globule sizes produced by the Heli-torch with its standard nozzle at heights of 20 metres or less will be between 60 and 120 mL. With gelling-mix-to-gasoline ratios of 2.5 to 5 kg per 205 L of fuel, such globules spread to thicknesses of 6 to 8 mm on oil-free water surfaces. The globule burn times range between 4 and 6 minutes.

Ignition of fresh and 2-week weathered, unemulsified crude oil layers is possible in winds of 15 to 25 km/h; globules approximately 60 to 120 mL in volume are necessary to prevent blowout of the flame. During several successful ignitions of crude oil slicks surface winds have reached speeds of 30 km/h.

Experience (Allen 1992) has shown that the Heli-torch should be flown at altitudes of 8 to 23 m and with speeds of 40 to 50 km/h. The suggested altitude range is to provide accuracy during the release, to reduce the loss of gelled fuel while burning in the air, and to prevent the blowout of smaller globules on the surface by downwash when the helicopter is flying at low speeds. A minimum speed of 40 km/h is recommended to prevent such blowouts. At altitudes in excess of 30 m downwash is minimal and the Heli-torch can be used in a stationary mode.

It should be noted that some jurisdictions/operators now restrict use of Heli-torch and other helicopter-slung devices, notably Norway.

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[1] Also known as FireTrol, EZFire, PetroJel, Alumagel

Table 4 gives a summary comparison of the two aerial ignition systems discussed above.

Table 4. Summary of Aerial Igniter Characteristics and Performance

ASSESSMENT CRITERIA		DOME IGNITER	HELI-TORCH (205 L MODEL)
SAFETY	Open flame or sparks inside aircraft	None, if EEIS used.	None
	Susceptibility to accidental activation	Highly unlikely: requires separate ignition source.	Unlikely: positive off/on control and isolated circuit breaker.
	Retrieval and handling of igniters that have misfired	Safe to handle after 2-min. delay.	Must return to base to adjust/ repair/replace Heli-torch.
STORAGE	Shelf life	5 years (Dome igniters stored 25 to 30 years in Arctic still operating).	N.A.: Flammable mixture prepared at time of need.
	Difficulty of replacement (all or in part) following normal shelf life	Simple replacement of pyrotechnic portion only (about 50% of initial <cost).	N.A.
	Routine maintenance requirements	None	Minimal: pump, valves, stirring equipment, etc.
	Susceptibility to high or low temperatures during storage/transit	Very low: tested between -70°C and +50°C.	Gel-mixing process best carried out at or above freezing temperatures.
	Susceptibility to vibration or humidity during storage/transit	Very low (meets military requirements).	Vibration not an issue. Fuel must be kept free of water prior to and during mixing.
GOVERNMENT REGULATIONS	Shipping and storage regulations	Basically treated as fireworks. Housed and locked in non-sparking container, properly marked as fireworks. Shipment by land, sea or chartered aircraft permitted; shipment by commercial passenger aircraft prohibited.	Subject to same storage and transit requirements as for petroleum products. Cannot fly Heli-torch over populated areas (FAR Part 137approved).
AVAILABILITY	Currently stockpiled	Approx. 1,700 igniters at Prudhoe Bay (owned by Alaska Clean Seas); approx. 4,000 igniters at Tuktoyaktuk, Canada (owned by Canadian Coast Guard).	Numerous units available in U.S. and Canada.
	Resupply capability	No longer produced by Energetex	Under emergency conditions, approx. 20 Heli-torches per month.
COST	Estimated cost	No longer produced by Energetex. Cost \$80 to \$120 (depending on volume purchased) per unit in 1986.	Approx. \$15,000 per application unit.
OPERATIONAL CONSIDERATIONS	Level of field testing performed to data	Extensive. Many controlled spills and some actual spills.	Extensive experience on land. Moderate experience with fresh oil on water.
	Reliance upon unique airborne application device	None	Yes. Heli-torch frame and pump assembly.
	Igniter (and/or application system)	None	Minor setup. Self-contained package quickly prepared and sling-loaded. Need mixing operations on ground for

ASSESSMENT CRITERIA		DOME IGNITER	HELI-TORCH (205 L MODEL)
	preparations – from storage to field use		support.
	Average rate of application	Approx. 3 to 6 per min.	Burning globules (golf ball to fist size) over a swath 3 m wide; typically about 2-km runs per sortie at 40 to 50/h and at 15 m altitude or less.
	Approximate number of igniters releasable per helicopter sortie	Several hundred depending on helicopter selected and ability to set down for transfer of cargo and passenger area.	Thousands of 60 to 120 mL globules.
	Accuracy of deployment on target oil slick	Excellent. Irregular shape prevents rolling. Low drift while airborne.	Random distribution of burning gel over target area.
	Durability (or resistance to damage during impact)	Good. Designed for typical drop heights of 15 to 30 m onto frozen surface.	Burning globules flatten out on impact with water.
OTHER	Performance in shallow pools (less than 4 in. deep) on solid ice	Good. Shallow draft.	Good
	Dependence on orientation for proper performance	Either of 2 stable, floating positions.	N.A.
	Nature and orientation of flame during ignition of oil	Hot, initial flame then soft, billowy flame concentrated over oil/water surface between floats.	Soft flame from gelled fuel globule: 15 cm diameter.
	Splash effects during impact with oil and water	Significant, though oil layers greater than 2 mm quickly become re-established around igniter.	Minimal, does not extinguish flame.
	Temperature and duration of heat source	More than 1200°C for 10 seconds followed by 700° C to 800°C for approx. 10 minutes.	Approx. 800° C for up to 6 minutes.
	Reliability of starter	Typically greater than 95%.	Unknown, but high
	Reliability of igniter	Typically greater than 90% (begins to drop after 5-year shelf life).	Unknown, but high
	Sensitivity to temporary submergence upon impact	None	Extinguishes
	Sensitivity to wind, rain and sea state during ignition	Blowoff wind velocity > 40 km/h., insensitive to rain, unknown sensitivity to waves.	Blowoff wind velocity for small globules < 10 km/h.; for larger globules> 30 km/h; insensitive to rain; unknown sensitivity to waves (successful with slightly weathered oil in 0.6 m waves).
	Type and amount of debris after use	Entire metal float package and fuel basket survive fire and remain on water surface.	No debris.
	Training requirements	Minimal (about 10 min.) Experience needed in identifying and hitting appropriate targets.	Moderate training both for operation and mixing fuel.

The key physical characteristics of past and present igniters that were designed and built specifically for ISB operations are summarised in Table 5.

Table 5. Past and Present Manufactured Igniters

Name	Size (cm)	Weight (kg)	Surface-deployed	Aerially-deployed	Firing mechanism	Firing delay (s)	Igniter flame T (°C)	Flame area (cm^2)	Flame time (min)	Safety	Field Proven	Presently available
Kontax	4 x 30.5	1.2	Yes	No	Water contact	0	770°C	3000	1 to 2	Not safe on water	Yes	No
EPS/Pyroid	25 x 25 x 13	2	Yes	Yes	Pull pin	25	≈2000	≈2500	2	Safe in 1980	Yes	No
ESSM	40 x 10 x 10	1.5	Yes	No	Electric filament	150 to 300	≈1370	?	2 to 3	Met SUPSALV requirements in 1996	No	No
Dome	30 x 18 x 11	0.4	Yes	Yes	Fuse	45	700 to 800	100 to 200	10	Safe in 1980	Yes	Stockpiles from 1980s
Helitorch	300 x 200 x 125	243	No	Yes	Propane flame	0	700 to 800	130 to 250	4 to 6	FAA Part 137 approved	Yes	Yes
AFTI	30 x 40 x 30	6	Yes	No	Marine flare	60 to 120	700 to 800	18,000	5	Non-hazardous until filled	No	Yes
Elastec Safe Start	20 x 20 x 30	3	Yes	No	Marine flare	60 to 120	700 to 800	10,000	5	Non-hazardous until filled	Yes	Yes
Simplex 901	20 x 10	0.5	Yes	No	Marine flare	60	700 to 800	1000	Up to 5	Non-hazardous until filled	Yes	Yes

2.4.3 *Fixed-Wing Aerial Ignition System*

The ignition of spilled oil from a fixed-wing aircraft has some significant advantages over hand-held igniters and the use of the Helitorch. Primary advantages include the ability to carry much larger payloads, typically approaching 1,000 gallons of gelled fuel, and to deliver such payloads many tens to hundreds of miles from a staging area. A series of "Proof-of-Concept" ground tests (Preli, *et al.* 2011) were conducted in 2010 and 2011 to determine whether gelled fuel could be ignited and achieve a sustained burn at release speeds of 80 to 100 knots, corresponding to the speed of a small fixed-wing aircraft. The tests were conducted at the Beacon Training Center in Kenai, Alaska.

Numerous tests were conducted with a variety of nozzle/shroud configurations at temperatures between 7°C to well below freezing using a trailer-mounted wind machine to simulate the release of various mixes of gelled fuel (gasoline, diesel, and aviation gas) gelled with Flash 21 gelling agent. The nozzle/shroud configurations were tested under a variety of orientations downwind to reduce the relative velocity of the burning gelled fuel globules within the wind-induced (aircraft-simulated) air. Over two separate week-long test periods the results demonstrated the feasibility of igniting gelled fuel at simulated fixed-wing aircraft speeds approaching 110 knots.

The safe and effective aerial application of gelled fuel far offshore with large payloads and high delivery speeds could significantly enhance the ability to conduct controlled burns should spilled oil be spread over a large and remote area, with or without ice.

2.4.4 *Regulatory Requirements*

The shipping, storage and use of igniters for ISB will require meeting regulatory requirements. There may be regulations governing the shipment or storage of igniters or their components by land, sea or air and some may require special handling (e.g., "Dome" igniters were classified in the same group of hazardous materials as fireworks, Heli-torch fuel is a petroleum product such as gasoline and diesel, and the surface-deployed igniters marketed by DESMI, Elastec and Simplex are specifically designed to be non-hazardous containers that are filled and activated using easily-obtained components purchased commercially from local sources and added just before use).

The carriage and use of aerial igniters by aircraft (fixed or rotary wing) will likely require approvals from the relevant aviation authority. For example, the use of a Heli-torch in the United States requires that the pilot hold a current US Government training certificate, no passengers be in the helicopter during operations and the helicopter must avoid flying over populated areas.

The regulations governing the use of in situ burning as an oil spill response tool are the subject of a separate report in the IOGP JIP Series (http://www.arcticresponsetechnology.org/wp-content/uploads/2013/10/Report%207.2.1%20-%20STATUS%20OF%20REGULATIONS%20IN%20ARCTIC%20AND%20SUB-ARCTIC%20COUNTRIES.pdf).

CHAPTER 3. SUMMARY AND CONCLUSIONS

Successful ignition of oil slicks on water for ISB requires at least 2 to 3 mm of oil thickness to support combustion, an igniter that heats the oil layer above its Fire Point and provides an open flame to ignite the oil vapours, and effective flame spreading to cover as much as possible of the slick.

The presently-available igniters for ISB operations are summarised in Table 6. Of these, the four that depend on gelled fuel are commercially available: stockpiles of the Dome igniter have existed in Alaska and Northern Canada since the mid-1980s.

The three hand-held igniters employing gelled fuel require that gelling agent, fuel (gasoline or diesel) and a marine flare be added onsite in order to be made functional. Since they contain no hazardous materials prior to being readied, they can be shipped empty without the need for hazardous material handling and documentation. These igniters are suited to initiating ISB in fire booms on water with one or two units released in from of, or directly onto the contained oil.

The Helitorch is the only presently-available system for deploying a large number of ignition sources from the air over larger areas of a spill in a relatively short time. The Helitorch is suitable for use on oil contained on or among ice, contained by herding agents or contained by fire boom.

Table 6. Summary of Presently-Available Igniters for ISB

Name	Fuel	Components	Firing Method	Intended Use	History	
AFTI Igniter	Gelled gasoline and/or diesel (gel and fuel supplied by user)	Cardboard box containing two plastic 3.8 L jugs, polyethylene foam packing, ballast weight, receptacle for marine flare	Marine flare (supplied by used)	Activated by hand and surface-deployed, allowed to drift or placed into oil contained in towed fire boom.	Developed during Macondo spill in 2010	
Elastec Safe Start	Gasoline and/or diesel (fuel supplied by user)	3.8 L plastic jug pre-filled with non-hazardous gelling agent fitted with foam collar and receptacle for marine flare	Marine flare (supplied by used)	Activated by hand and surface-deployed, allowed to drift or placed into oil contained in towed fire boom.	Developed during Macondo spill in 2010	
Simplex Model 901 Hand-held	Gelled gasoline and/or diesel fuel, with demulsifier or anti-foaming agent additives (all supplied by user)	1 L plastic jug pre-filled with non-hazardous gelling agent fitted with foam collar and receptacle for marine flare	Marine flare (supplied by used)	Activated by hand and surface-deployed, allowed to drift or placed into oil contained in towed fire boom.	Developed in early 1990s after *Exxon Valdez* spill.	
Dome Igniter (stockpiled in Alaska and Canada)	Gelled kerosene	Metal juice can floatation, wire basket containing fuel, fuse for firing.	Safety fuse, igniter wire, solid propellant	Activated by hand and thrown from helicopter or surface-deployed, on to oil contained on ice or in fire boom	Developed in late 1970s/early 1980s for ISB on ice	
Helitorch	Gelled gasoline and/or diesel fuel, with demulsifier or anti-foaming agent additives (all supplied by user)	Frame, sling, 205-L drum, pump, valves, 28V power, controls, propane for lighter	Gelled fuel pumped past propane flame	Operated as a sling load under helicopter. Loaded and propane flame started on ground. Burning fuel released over target by pilot.	Adapted from forest fire fighting in early 1980s for ISB on ice and water	

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