A PRELIMINARY FEASIBILITY STUDY OF IN-SITU BURNING OF SPREADING OIL SLICKS

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ABSTRACT: *An experimental and theoretical preliminary feasibility study was conducted on the use of in-situ burning as a countermeasure for oil spills spreading on open water. This technique theoretically has the potential to remove a considerable percentage of the oil from such spills, providing ignition can be effected within several hours of the incident.*

Cases of tanker accidents where released oil caught fire and was consumed[3,4] suggest that in-situ burning may be an effective technique for dealing with thick oil spills on open water. The present work, supported by both Environment Canada and the U.S. Coast Guard, was undertaken to pursue this countermeasures approach. The objective was to determine whether ignition and burning of spreading oil slicks shortly after their release at sea is technically feasible.

Methods

Small-scale testing. Small-scale experiments to investigate oil spreading and flame spreading were conducted in a small wind tunnel in Ottawa, Ontario. A crude oil, Alberta sweet mixed blend, was weathered to three different degrees, simulating the exposure of a 3-cm-thick slick in a 10 m/s wind for one, four, and eight hours at 10° C. A fresh diesel oil also was used in the experiments.

The oil-spreading experiments involved the placement of 600 mL of oil in the upwind edge of a 3 m × 10 cm water trough in the wind tunnel. The oil, at a initial thickness of 2 cm, was retained by a removable rubber dam. Before each run, wind speed was measured, and air and water temperatures were recorded.

The spreading of the oil, released by raising the dam, was recorded on videotape and measured against a scale marked on the outside of the trough and visible through the plexiglass windows of the wind tunnel. For each of the four oils, flame spreading was measured as a function of wind speed (both upwind and downwind) for both a 3-mm-thick slick covering the entire trough and ignited at one end, and a 2-cm-thick slick of burning oil released as in the oil-spreading experiments. This preliminary study was not conducted in a properly scaled wind tunnel, and thus the results cannot be accurately scaled to real-world conditions.

Mid-scale testing. The mid-scale testing was conducted in an outdoor test tank in Waterloo, Ontario. The purpose was to investigate the combustion efficiency of uncontained slicks, two-dimensional oil and flame spreading, and combustion rate as a function of slick thickness.

The combustion efficiency and spreading tests involved a variety of fresh crude oils and diesel, initially contained in one- and two-meter-diameter metal rings on the water surface of the tank. The oil was ignited, then released by lowering the ring below the water surface. Spreading was recorded on videotape, and removal efficiency was determined by recovering and measuring the oil residue.

Combustion rate as a function of slick thickness was determined by igniting and burning contained oil slicks of varying thickness (up to 2 cm) and recording the burn time and volume of residue.

Large-scale testing. These tests were conducted in a 45 m × 67 m shallow test pit near Sohio Alaska Petroleum Co.'s East Dock facility in Prudhoe Bay, Alaska. At the center of the pit, a 30-cm-high, 6-m-diameter sheet-metal ring was balanced on four stakes and held in a circular shape by several stakes placed around the inside circumference of the ring.

Before each test, a specified volume of Prudhoe Bay crude oil was pumped into the ring through a submerged hose. Tests 1 and 2 were designed to measure oil and flame spreading and combustion efficiency for instantaneously ignited slicks. Test 3 was designed to measure combustion rate and air entrainment, and test 4 was designed to evaluate the effect of delayed ignition.

For tests 1, 2, and 3, the oil inside the ring was ignited using a propane weed burner. In tests 1 and 2, once the flames had spread to cover the contained oil, the ring was dropped by pulling out the supporting stakes using ropes from the sides of the pit. Each burn was recorded on videotape to document oil and flame spreading.

For test 3, two bidirectional pitot tubes[6] were placed about 15 cm from the outside of the ring, one on the upwind side and one on the downwind side, to measure entrained air velocities. The burning oil was contained within the ring for the duration of the test.

For test 4, eight baking trays, each supported on two stakes, were placed about 1 cm above the water, approximately 1 m from the outer edge of the ring, spaced evenly around the ring's circumference (about 3 m apart). An oil-soaked sorbent pad was placed in each tray, and the trays were filled with oil and ignited. Once all the trays were burning vigorously, the ring was dropped and the oil released.

After each test, the oil residue was collected and weighed.

Results and discussion

Small-scale testing. Figure 1 plots the oil spreading and the predicted spreading using Fay.[2] Figure 2 gives the same results plotted in the nondimensional form used by Fay. In both cases, the data follow the trend of Fay's model, but there is a definite oil viscosity effect not accounted for by the model. As the oil viscosity increases, the difference between actual and predicted spreading increases.

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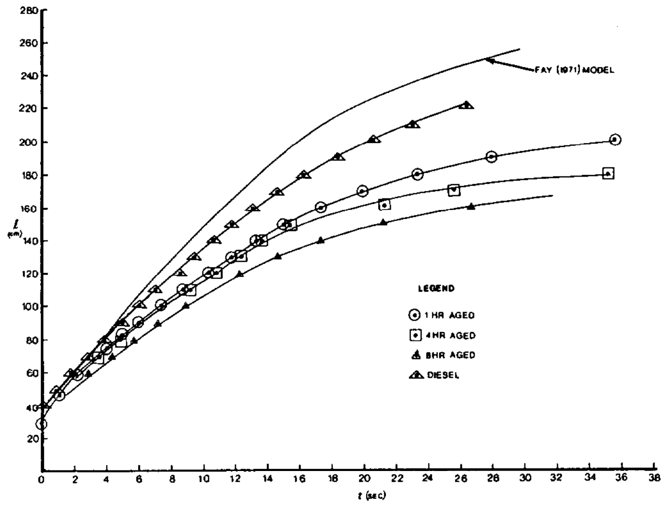

Figure 1. Actual and predicted spreading of oil with no wind

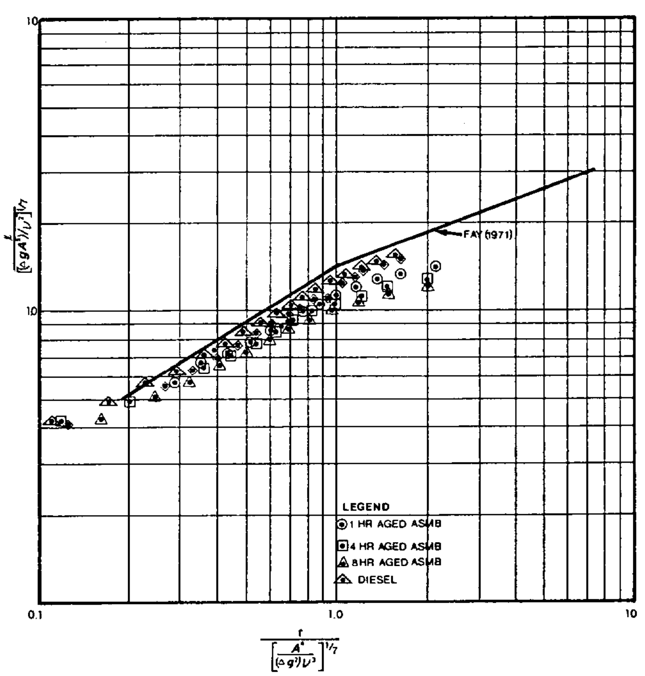

Figure 2. Results of oil-spreading tests plotted in nondimensional form

Oil spreading with wind. Of particular importance to this study was the wind speed required to balance the spreading force of an oil slick. At the equilibrium point, the spreading force of a static, one-dimensional oil slick in the gravity regimes is

$$F_s = (\rho - \rho_o)\ wgh^2$$

Where: F_s = spreading force (N)
ρ = water density (kg/m^3)
ρ_o = oil density (kg/m^3)
w = slick width (m)
h = slick thickness (m)
g = acceleration due to gravity (9.81 m/s^2)

and the force of the wind acting over the area of the slick is

$$F_w = C_D \cdot V \cdot \rho_A \cdot U^2/h$$

Where: F_w = wind-retarding force (N)
C_D = drag coefficient of slick
V = slick volume (m^3)
ρ_A = air density (kg/m^3)
U = wind velocity (m/s)

At equilibrium the two forces balance, i.e.,

$$C_D \cdot V \cdot \rho_A \cdot U^2/h = (\rho - \rho_o)\ wgh^2$$

or

$$h = (C_D \cdot V \cdot \rho_A/(\rho - \rho_o)\ wg)^{1/3} U^{2/3}$$

which can be rewritten as

$$h^3/V = (C_D \cdot \rho_A/(\rho - \rho_o)\ wg)\ U^2$$

Figure 3 plots h^3/V vs U for the wind tunnel tests. A plot of the equation above with $C_D = 3.5 \times 10^{-3}$ is also given. The equation fits the data quite well, except at low values of U where it considerably underestimates the experimental values. This is probably due to the end effects of the trough, where spreading ceases due to surface-tension effects in the finite test length.

Flame spreading over oil. All the oils tested exhibited similar results. In all cases, the data show that the flame velocity is constant for a given wind speed and oil type. Figure 4 shows the average flame velocity plotted against wind speed for each of the four oil types. The flame flashing velocity (the velocity at which flame propagates through a combustible mixture of vapors) was measured at 1.3 m/s. Although the data were collected in a rather primitive wind tunnel and thus cannot be scaled, the results conform with those obtained by later large-scale studies.[1]

The final form of the equation for downwind flame spreading is

$$U_{Fd} = \exp\ (6.52\ (T_B - T_A/T_B)^{0.23})U + 1.3\ \exp(-7.88\ (T_B - T_A/T_B)^{0.19})$$

Where: U_F = flame velocities (m/s)
T_A = ambient temperature (K)
T_B = initial boiling point of the oil (K)

Although upwind flame spreading velocity is a weak function of wind speed, for the purposes of this work it can be assumed to be independent of wind speed. Thus:

$$U_{Fu} = 1.3\ \exp\ (-7.88\ (T_B - T_A/T_B)^{0.19})$$

Combined oil and flame spreading. Several runs were performed to investigate oil and flame spreading combined. For these, burning oil was released at the end of the trough and the spread of both the oil and flame recorded.

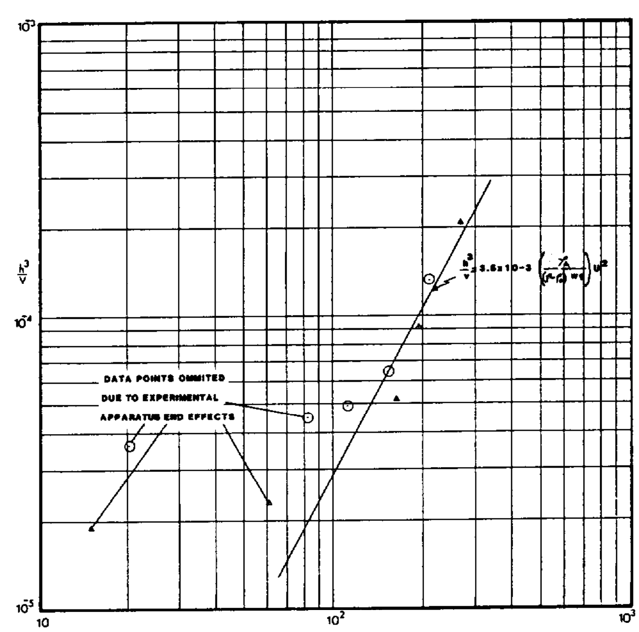

Figure 3. Wind drag coefficient determination

With all the crude oils tested, the flame kept up with the oil spreading over the entire range of wind speeds tested. It is interesting to note that the burning oil did not spread appreciably faster nor farther than did cold oil. Only in the case of the diesel fuel did the flames not keep up with the spreading oil, and then only at tunnel wind speeds of less than 1 m/s.

Mid-scale testing. Figure 5 plots the measured average regression rate (total volume burned/time from ignition to extinction) against initial slick thickness for the contained burns. Also shown are the data from Wakamiya et al.[10] for a variety of crude oils in two-meter-diameter pans, and the results of McAllister and Buist[5] from a two-hour test burn in a fireproof boom (2.6 m diameter). It can be seen that, first, slicks with a thickness greater than about 5 mm burn at a rate independent of thickness; second, 2-m-diameter slicks burn slightly faster than 1-m-diameter slicks, but for slicks greater than 2 m in diameter the burning rate does not seem to be a strong function of slick size; and third, (as shown by Wakamiya et al.[10]) slicks seem to burn faster at higher ambient temperatures (about 15% faster for an average 15° C rise in temperature).

The rapid reduction in regression rate with decreasing thickness below about 5 mm is confirmed by the data of Wakamiya et al.[10] and is likely due to increasing heat transfer to the underlying water. A good estimate for the regression rate for large (>2 m), thick (>5 mm) oil slicks on water would be about 2 to 2.5 mm/min.

Removal efficiency. Table 1 shows the results of the tank tests of uncontained slick combustion. The residue of Run 11 was highly emulsified and no removal efficiency could be calculated. In all the tests, with the exception of those involving diesel, the flames kept up with the spreading oil until it reached a thickness of about 1 mm.

Large-scale testing. Table 2 summarizes the conditions and results of each of the tests.

Oil and flame spreading. For test 1, unfortunately, the oil was ignited on the downwind edge, and it took about 90 seconds for the flames to spread. After the test, it was determined that the oil within

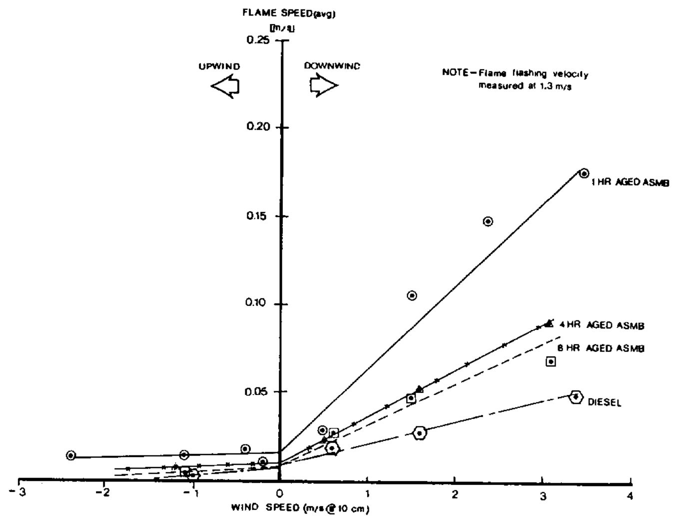

Figure 4. Flame spreading velocity

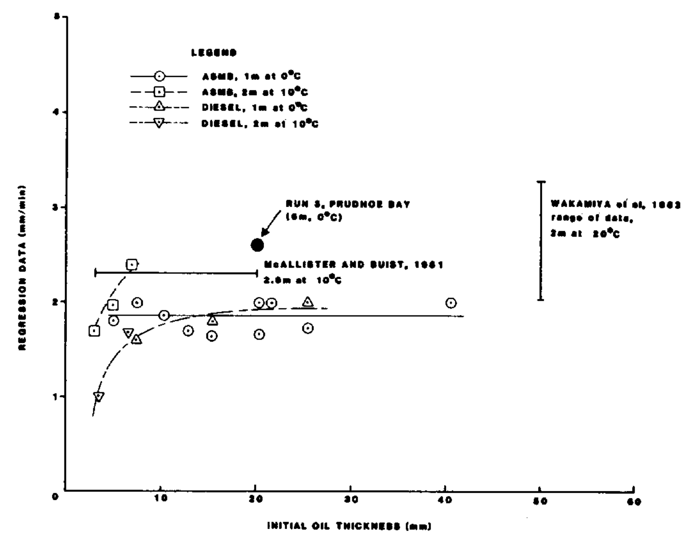

Figure 5. Comparison of slick regression rates (contained burns)

Table 1. Uncontained oil slick—combustion results

Test no.	Oil type	Oil volume (L)	Water area (m^2)	Ring diameter (m)	Oil residue (L)	Combustion efficiency (%)	Preheating time[1] (min)	Burning time (min)	Comments
1	Lloyd	4	24	1	3.8	0			
2	Lloyd	6	24	1	4.3	28.0	0:20	2:00	
3	Lloyd	10	24	1	4.5	55.0	0:30	1:00	
4	Lloyd	14	24	1	7.0	50.0	0:55	0:35	
5	Norman Wells	8	24	1	3.0	62.5	0:37	0:51	
6	Norman Wells	12	24	1	4.5	12.5	0:15	0:50	
7	Norman Wells	16	24	1	6.0	62.5	0:20	0:45	
8	Norman Wells	16	48	1	7.0	56.0	0:25	0:45	
9	Norman Wells	20	24	1	8.0	60.0	0:20	0:60	
10	Diesel	8	24	1	6.3	21.0	0:45	0:50	
11	Diesel	14	90	2	20.0	?	1:10	0:60	residue emulsified
12	Diesel	20	90	2	13.6	32.0	1:35	0:30	
13	ASMB	10	90	2	5.8	42.0	0:50	0:35	
14	ASMB	20	90	2	6.3	68.5	0:10	0:40	
15	ASMB	26	90	2	8.4	67.6	0:25	0:40	

1. Time from ignition to oil release

Table 2. Results of large-scale test burns

	Test No.			
	1	2	3	4
Initial oil volume (L)	958	1,343	575	1,273
Initial oil weight (kg)	857	1,200	342	1,140
Initial oil thickness (mm)	33	47	20	40
Ignition and release	ignited and released	ignited and released	ignited, not released	released, then ignited
Wind speed (m/s)	2	2.5	0–2	2.5
Air temperature (°C)	−1	2	0	1
Water temperature (°C)	0	0	0	0
Residue oil volume (L)	N.M.₁	120	N.M	N.M.
Residue oil weight (kg)	240	109	62	133
Combustion efficiency (wt. %)				
Total	72	90.9	87.9	88.3
Corrected₂	70.9	90.6	—	—

1. Not measured
2. Initial oil volume reduced by amount burned before dropping ring

the ring had not been completely on fire when released. Only about 75% of the surface area was covered. Between the time of release and extinction, the slick drifted about 10 m in 150 sec (10 cm/s), at about 3% of the wind speed.

Figure 6 shows the calculated oil and flame areas for test 1. Also shown are the predicted oil slick area[2] if no combustion were occurring, and the predicted area of combustion using equations developed to describe the spreading of burning oil.[8]

The difference between actual and predicted slick spreading may be because the inflow of air to supply the combustion slowed the oil spreading. The predicted flame area differs from the actual because the model is based on instantaneous ignition of the entire slick area. In test 1 only 75% of the slick was on fire when it was released.

Figure 7 shows the predicted and calculated oil and flame areas as a function of time for test 2. In this case, Fay's model[2] only slightly overestimates the initial oil spreading; however, it can be seen that once the flames reached an area of about 300 m^2, the oil spreading was retarded for about 30 seconds, likely due to the effects of the induced flow of air into the fire. The predicted flame area does agree fairly well with the observed flame area. Figure 8 compares the calculated flame area for test 4 with that predicted by the burning model and Fay's oil spreading model. Taking into account the delay in ignition, the predicted and actual flame spreading are quite close.

Air entrainment and self-induced wind-herding. Figure 9 shows the results of the airflow measurements, upwind and downwind of the fire, in test 3. The upwind pitot tube measured a definite induced airflow, with a velocity of about 30 cm/s greater than the ambient wind. The difference in ambient wind speed measured before and after the test may be a result of the light variable winds at the time of the test, combined with zero-drift in the electronic manometer and/or chart recorder.

The downwind pitot tube recorded highly turbulent airflows. This fact was confirmed visually by the presence of "dust devils" downwind of the fire. In fact, the downwind pitot tube may have been immersed in flame for much of the burn, and the apparent increase in downwind velocity by about 10–15 cm/s may be a component of the buoyant rise velocity of the diffusion flame being bent over by the wind.

The average of the upwind and downwind measurements is a net inflow of air at about 14 cm/s. This agrees with the data of Thomas et al.[9] for air entrainment into gas burners (about 17 cm/s, 0.25 m above the base of the flame) and with the theory of McCaffrey,[7] which predicts velocities of 20–25 cm/s at the same height and radius.

To model the effects of self-induced wind herding of a burning oil slick, the spreading force of the slick (assumed to be gravity for the slicks of interest) is balanced by the drag on the slick of the radially inward surface current induced by the entrained airflow, i.e.,

Gravity force per unit volume = drag force per uit volume, or

$$(\rho - \rho_o)\, gh/\pi^{1/2} r = C_D \rho_A A U^2/V$$

Where: r = slick radius (m)

substituting $V = Ah$, and rearranging the equation yields

$$h = (\pi^{1/2} C_D \rho_A/(\rho - \rho_o)\, g)^{1/2} U r^{1/2}$$

It can be shown that, for very large fires, U is a constant equal to about 0.25 m/s. Thus, substituting the value for C_D from the wind-tunnel tests and $(\rho - \rho_o) = 105$ kg/m^3 yields

$$h = 7 \cdot 10^{-4} r^{1/2}$$

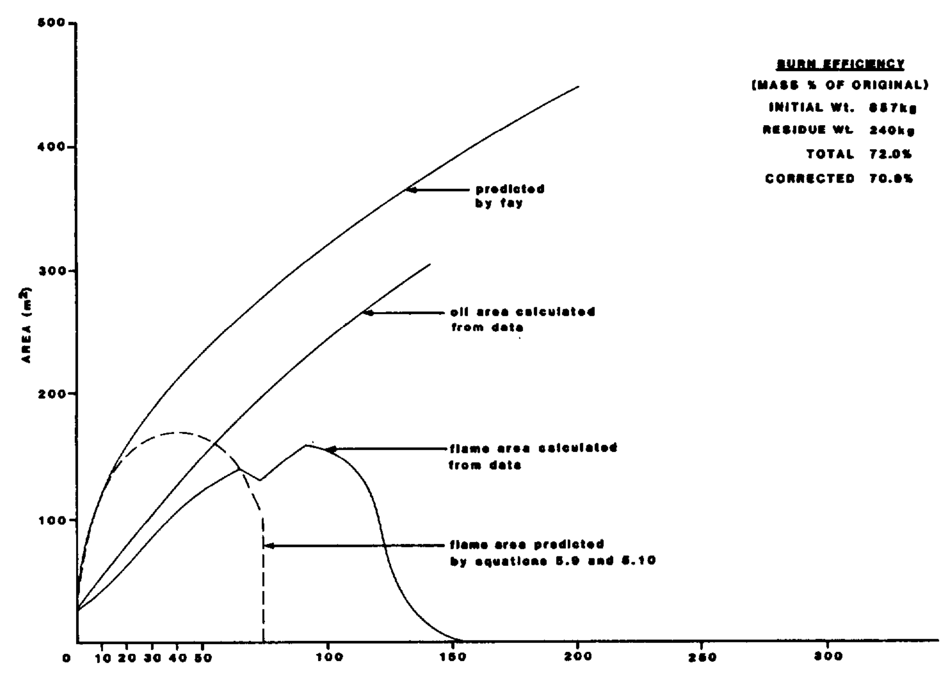

Figure 6. Calculated oil and flame area, test 1

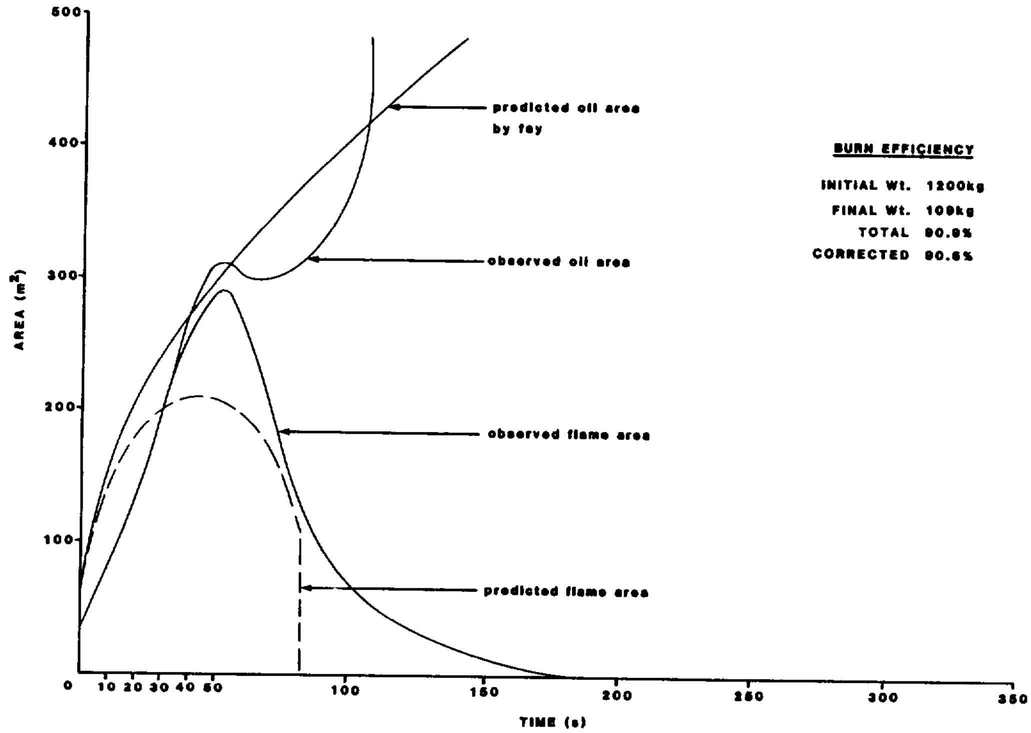

Figure 7. Calculated oil and flame area, test 2

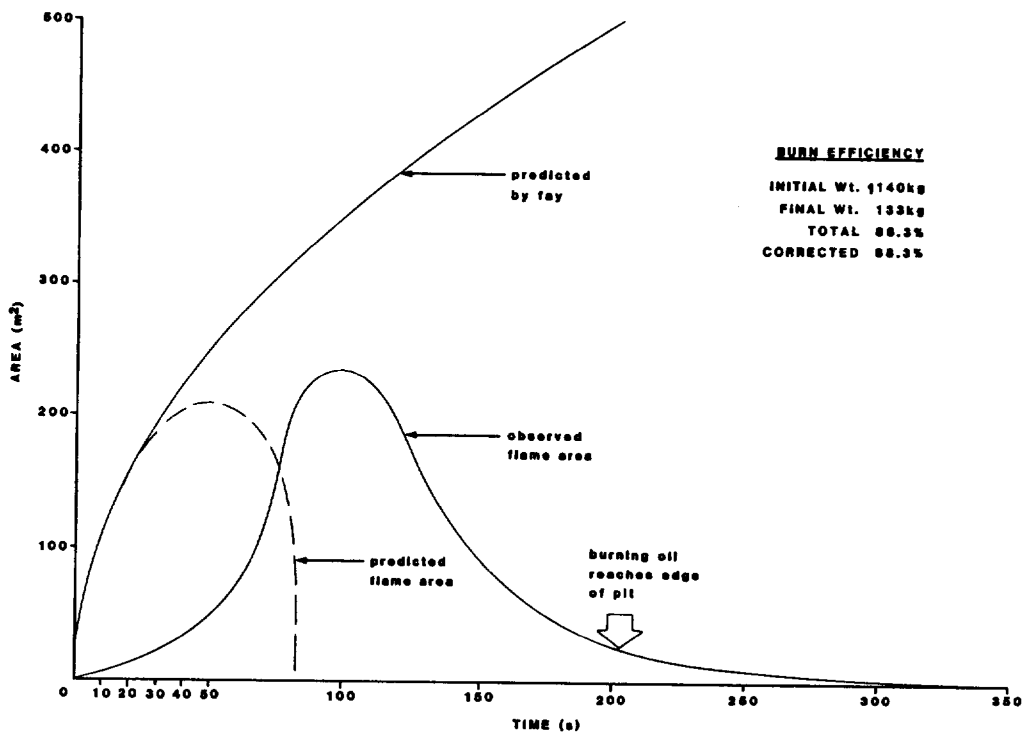

Figure 8. Calculated flame area, test 4

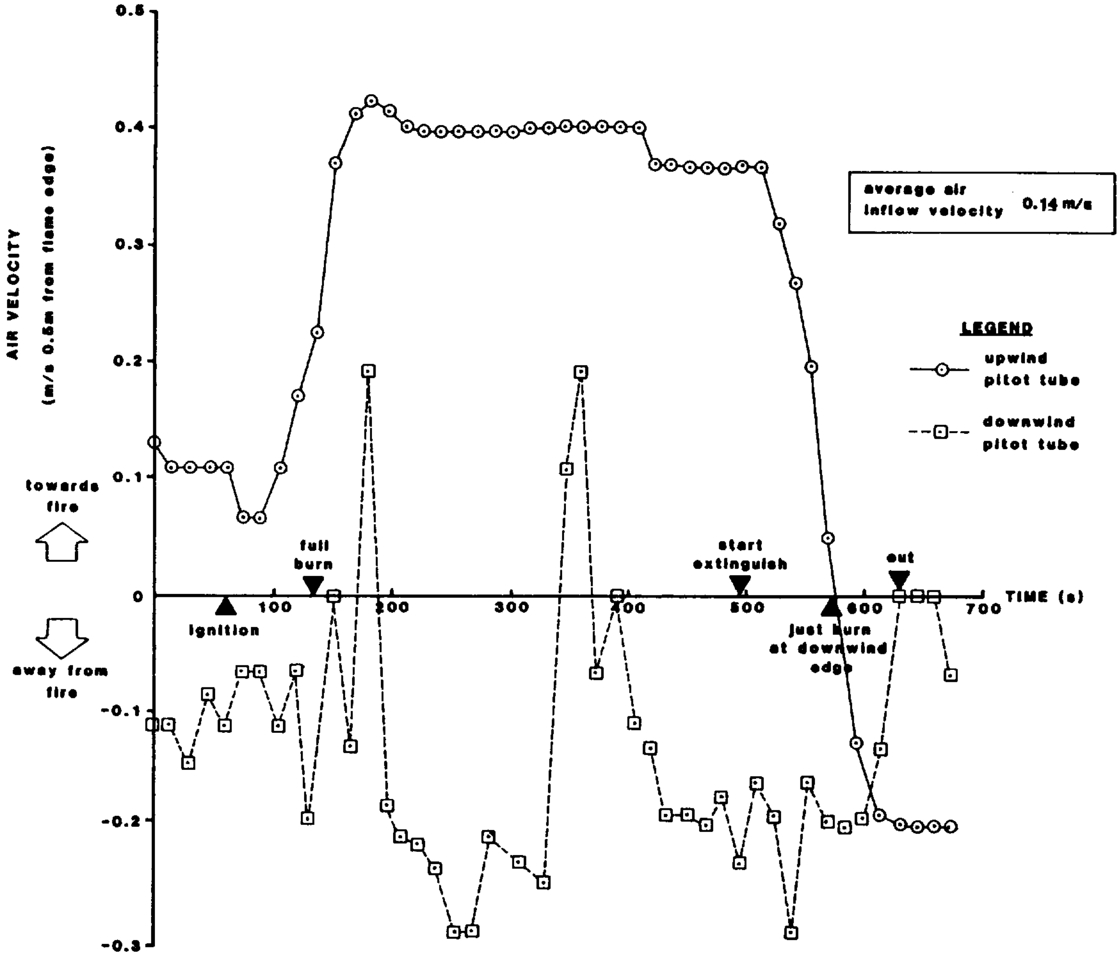

Figure 9. Airflow measurements, test 3

This provides only an estimate of the slick thickness because of the difficulties in translating data obtained in the wind tunnel to the real world.

This equation predicts a self-induced wind-herded slick thickness of 2.2 mm for a 10 m radius (300 m^2 area) slick, which agrees well with the data for test 2 (Figure 7) indicating a cessation of oil spreading at 300 m^2 with an estimated thickness (including oil losses to combustion) of 3 mm.

Combustion efficiency. Figure 10 shows combustion efficiency as a function of oil volume for both the large-scale and mid-scale tests. In general, as oil volume increases, so does combustion efficiency. Comparison of the large scale data points indicates that:

- Instantaneous ignition of the entire slick area results in a higher combustion efficiency than delayed ignition of the periphery (90.6% vs 88.3%).
- Ignition of the entire surface area or of the full circumference of the spreading oil is more efficient than ignition of a portion of the downwind slick.

This last point is important for oil spill burning operations. It seems that, unlike oil contained against a fixed barrier, the upstream oil is not fed by wind into the downstream area on fire. In the case of test 1 (where about 25% of the upwind area of the slick in the containment ring was not on fire upon its release), the burn efficiency was measured at about 75% of that in test 2, when the entire slick area was on fire upon release. It seems that a thick, free-floating slick, in the absence of large-scale eddies, is advected en masse by the wind-driven surface currents, and unignited oil is not pushed into the fire zone. Since upwind flame spreading rates are low (1–2 cm/s), it is unlikely that oil, upwind of a floating ignition source drifting with the slick, would be ignited. Thus, it is important to ignite the upwind extremities of a thick slick.

Modeling the burning of unconfined oil slicks

The spilled oil is assumed to spread according to the well-known laws formulated by Fay:[2] initially a gravity-inertial spread with slick radius proportional to $t^{1/2}$, followed by a gravity-viscous spread with slick radius proportional to $t^{1/4}$. The subsequent surface-tension viscous spread is not dealt with because the transition to that regime is uncertain and may occur when the slick is too thin to burn.

The combustion process is assumed to affect the spread of the slick in only one way, namely that the air flowing into the flame induces a water surface current that opposes the spreading of the slick. This is the self-generated "wind-herding" phenomenon.

The slick continues to burn until its thickness reaches some minimum value, at which point the heat loss to the water uses up all the heat feedback to the slick from the flame above it. The experimental value for this minimum thickness is about 0.8 mm. The combustion efficiency of the slick is the difference between the volume of the oil spilled and the volume of the remaining layer of unburned residue that has that thickness, divided by the volume of oil spilled. For any given spill volume, the combustion efficiency is maximum when the slick is ignited immediately. Delaying ignition decreases the efficiency. If ignition is delayed until the slick thickness is less than 0.8 mm, none of the oil can burn, and the combustion efficiency is zero. Details of the model may be found in the project report.[8]

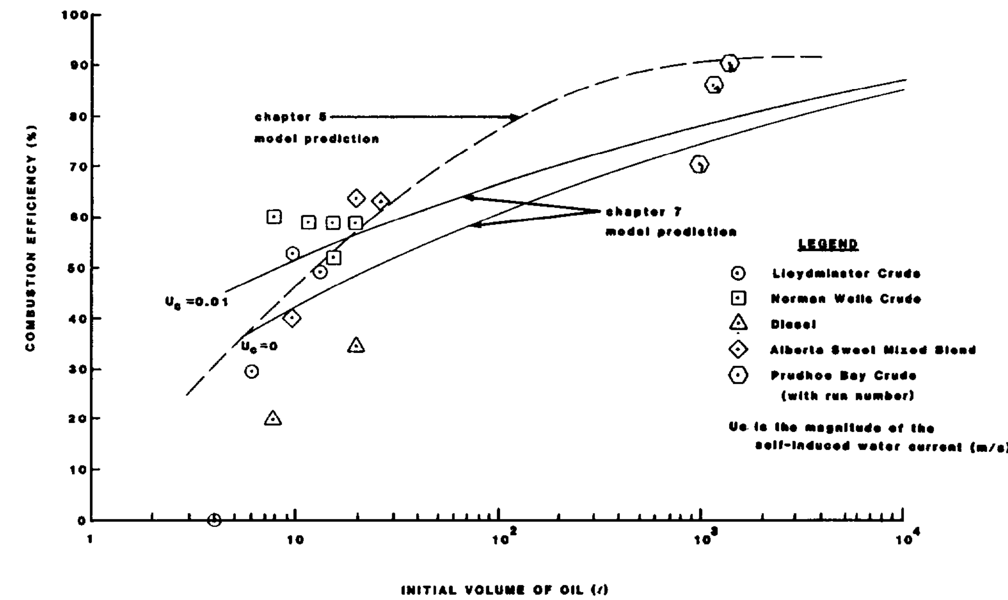

Figure 10. Combustion efficiency—instantaneous ignition

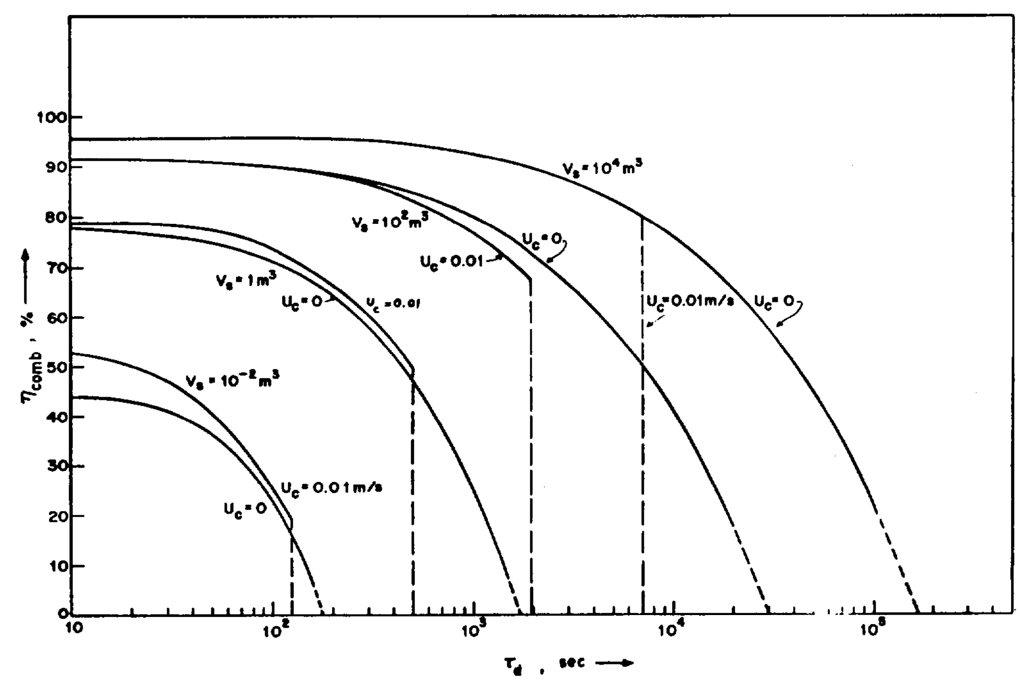

Figure 11. Combustion efficiency as a function of ignition delay

Results

Combustion efficiency for immediate ignition. The computed combustion efficiency (η_{comb}) as a function of spill volume is shown on Figure 10. The effect of the induced current is to increase the burning time and the combustion efficiency and to decrease the size of the slick when burning cease. A rough estimate of η_{comb} can be obtained from

$$\eta_{comb} = (1 - 1/3\ V^{-1/5}) \cdot 100\%$$

Combustion efficiency with ignition delay. The computed values for combustion efficiency are plotted in Figure 11 as a function of the ignition delay (τ_d). Four pairs of curves are shown, one for each of the following values of V: 10^{-2}, 1, 10^2 and 10^4 m^3.

One curve in each pair was calculated for zero induced current ($u_c = 0$). The other was calculated for $u_c = 0.01$ m/s. In each case, the combustion effciency decreases from a maximum value at the smallest delay. The values shown for $\tau_d = 10$ are for all intents and purposes the same as those for zero delay.

In the case of zero surface current, the curves of η_{comb} approach zero continuously. With $u_c = 0.01$ m/s, the curves were very simular to those for $u_c = 0$, up to a point. At a certain value of τ_d, the equations could no longer be solved. The slick thickness began to increase, the slick radius decreased, and the burning rate began to decrease drastically. This behavior occurred for all higher values of τ_d.

The actual value of u_c very likely lies between 0 and 0.01 m/s (assuming the surface water moves at 3% of the wind speed, the value of u_c measured during the large-scale trials was $0.14 \cdot 0.03 = 0.004$ m/s). This means that in practice at least a rapid decrease of η_{comb} could be expected with delay time beyond the threshold value.

The threshold value of τ_d is identified as the maximum possible delay in igniting the slick. If ignition is delayed any longer, burning may be ineffective. The values of the maximum ignition delay are listed in Table 3. Also included are x_q (the dimensionless radius at extinction), τ_q (the burn time), and η_{comb} for the maximum delay.

Table 3. Maximum ignition delay $\tau_{d,max}$ and corresponding τ_q x_q and η_{comb}

		at τ_d, max		
V (m^3)	τ_d, max(s)$_1$	τ_{q_2}	x_{q_3}	η_{comb} (%)$_4$
10^{-2}	125	190	8.322	19.3
1	500	665	14.127	49.8
10^2	1,950	2,312	24.392	68.0
10^4	7,150	7,830	41.555	79.8

1. Maximum permissible delay between spill and ignition
2. Burn time
3. Dimensionless radius at extinction
4. Computed combustion efficiency

The maximum permissible ignition delay can be correlated with spill size. An excellent correlation is obtained in the form of a power law. In dimensional form it can be expressed as

$$t_d,max = 0.0975V^{0.46}$$

Where: t_d,max = maximum permissible delay time (hours) between occurrence of the spill and its ignition

This equation is plotted in Figure 12. A rough but useful approximation of this equation is

$$t_d,max = 0.1\ V^{1/2}$$

The delayed ignition of a spreading slick is accomplished by placing igniters around its perimeter. The flame spreads outward with the burning oil. Its inward spread is aided by the inward wind induced by the flames at the periphery.

Igniters could be placed three meters apart around the perimeter of the slick. The slick radius at t_d, max is one of the results of the model calculations. Therefore, the number of igniters needed to achieve ignition with the maximum permissible delay can be estimated. The results are presented in Table 4.

Table 4. Number of igniters needed at the maximum ignition delay

V (m^3)	Number needed
10^{-2}	4
1	30
10^2	238
10^4	1,875

These results are also well correlated by a power law

$$N = 31\ V^{0.45}$$

This equation is also shown on Figure 11.

Additonal results are presented in the project report.[8] They include the derivation of the equation, and scaling factors for time and slick radius, and the parameters of the slicks whose behavior was calculated.

Conclusions

- The ignition and burning of umcontained batch oil spills seems to be a feasible countermeasure for certain open water spills.
- Combustion efficiency is primarily a function of spill volume; the larger the spill the higher the combustion efficiency (about 90% for spills of 1 m^3 ignited instantaneously). A rough approximation of the theoretical combustion efficiency for an instantaneously ignited slick is
  $$\eta_{comb} = (1 - 1/3V^{-1/5}) \cdot 100\% \text{ (with V in m}^3\text{)}$$
- The sooner a slick is ignited, the higher the combustion efficiency. The theoretical maximum permissible ignition delay can be estimated by
  $$t_d,max = 0.1\ V^{1/2} \text{ (with } t_d\text{,max in hours, V in m}^3\text{)}$$
- Ignition of the periphery of the slick results in combustion efficiencies almost as high as those for ignition of the entire surface area. The required number of conventional igniters spaced three meters apart at the maximum ignition delay, extrapolated from one test, can be estimated by:
  $$N = 31\ V^{0.45} \text{ (with V in m}^3\text{)}$$
- Air, entrained by the combustion of the oil slick at a velocity of about 0.14 m/s, induces an inward surface current that inhibits and finally stops the oil's spread. The slick thickness at which this occurs is related to the size of the fire and can be theoretically estimated by
  $$h = 7 \cdot 10^{-4} r^{1/2} \text{ (with h and r in m)}$$

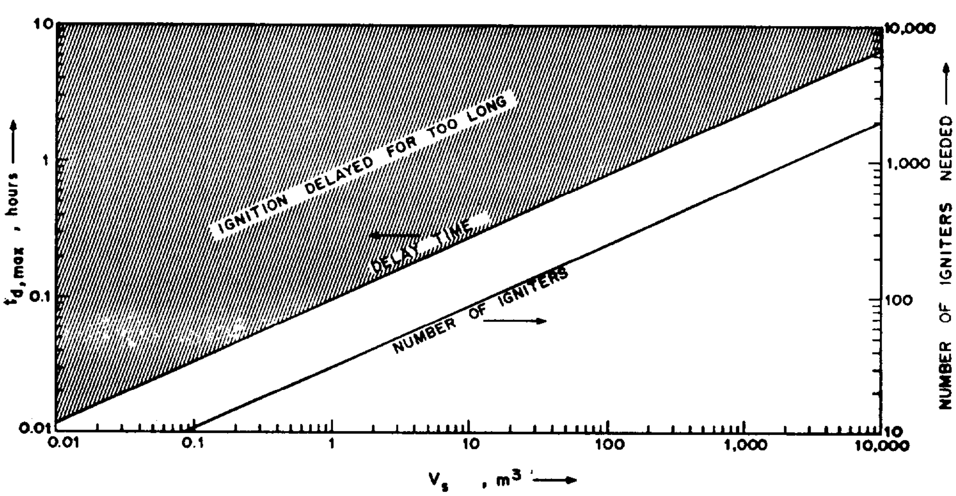

Figure 12. Maximum permissible ignition delay time and number of igniters required as a function of spill volume

Recommendations

Key areas of research that need to be addressed more rigorously than was possible in this preliminary study are flame spreading over a variety of oils, flame-induced air entrainment, and the maximum possible igniter spacing around a slick perimeter. Larger-scale tests are needed to assess the theoretical extrapolation of the test results.

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