IN-SITU BURNING OF UNCONTAINED OIL SLICKS

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INTRODUCTION

Previous studies have concluded that little can be accomplished with a conventional land-based cleanup operation in response to a major tanker spill in open water in remote areas, and that in-situ burning of oil contained by ice appears to offer the only opportunity to remove significant amounts of spilled oil (S.L. Ross, 1982, 1983a 1983b). Studies of on-board, self-help cleanup technology for tankers have also concluded that presently available systems can only recover an insignificant amount of a major oil release (S.L. Ross, 1983b, Environment Canada, 1984). However, cases of tanker accidents where the released oil caught fire and most of it was consumed (e.g. Goodier and Siclari, 1981; Horn and Neal, 1981) suggest that in-situ burning may be an effective tanker-based response.

The present work, supported by both Environment Canada and the United States Coast Guard, was undertaken to pursue this counter-measures approach by investigating the capabilities and limitations of igniting and burning large uncontained oil slicks at sea. The objective was to determine whether or not in-situ combustion of oil released from damaged tankers is a technically feasible countermeasure for open water conditions. Key areas of the burning of uncontained oil slicks that were addressed are:

* oil spreading on water,
* flame spreading on oil,
* combustion efficiency of spreading oil slicks, and
* the effects of delays in ignition of the oil

The premise of the study was based on the idea that, if a large, thick slick of oil is ignited, and the flames spread to cover the majority of the slick before it thins to less than one millimetre, very high oil removal efficiencies are possible. As the fire grows it can be postulated that the air entrained by the combustion and the thermal plume reduce the spreading rate of the oil and, at some critical fire size, stop the spreading, resulting in potentially very high oil combustion efficiencies.

EXPERIMENTAL METHODS

There are three portions to the experimental study involving small-scale, mid-scale and large-scale work. The first two have been completed; the large-scale phase has yet to be done. The work was performed at two locations, Ottawa and Waterloo, Ontario.

Environment Canada. Arctic and Marine Oilspill Program (AMOP) Technical Seminar, 7th. Proceedings. June 12-14, 1984, Edmonton, Alberta, Canada, Environment Canada, Ottawa, Ontario, 127-154 pp, 1984.

Small-Scale Testing

The small-scale experiments, to investigate oil spreading and flame spreading, were conducted in a small wind tunnel in Ottawa, (Figure 1). A crude oil, Alberta Sweet Mixed Blend (provided by Petro-Canada), 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 was also used in the experiments. Table 1 gives the physical properties of the four oils.

The oil spreading experiments involved the placement of 600 cm^3 of oil in the upwind edge of a 3m long x 10 cm wide water trough in the wind tunnel. The oil was retained, at an initial thickness of 2 cm, by a removable rubber dam. Prior to each run the wind speed was measured, using a thermal anemometer, 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 visible through the plexiglass windows of the wind-tunnel. Time, in hundredths of a second, was recorded by a built-in display timer in the video-camera. The trough was cleaned thoroughly after each run to minimize the effects of surface films on spreading rates.

Thirty-three runs involving the four oils at wind speeds of 0, 0.2, 0.6, 3.8 and 8.0 m/s (with spreading both up and downwind) were conducted.

Flame spreading on each of the four oils was investigated in two ways. Flame spreading as a function of wind speed (both upwind and downwind at 0.2, 0.5, 1.6 and 3.1 m/s) was measured using the videotaping technique 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. A total of 39 runs were undertaken, including several at different temperatures (1° C, 10° C and 19 ° C).

Mid-Scale Testing

The mid-scale testing was conducted in an outdoor test tank in Waterloo. Its 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 metre 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 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

Originally it had been planned that this phase of the program would involve large-scale uncontained burns in a small pond or quarry to obtain data on combustion efficiency, spreading and in particular the effects of ignition delay. The burns were to involve $2m^3$ of oil each, spreading to

FIGURE 1

Wind Tunnel Apparatus

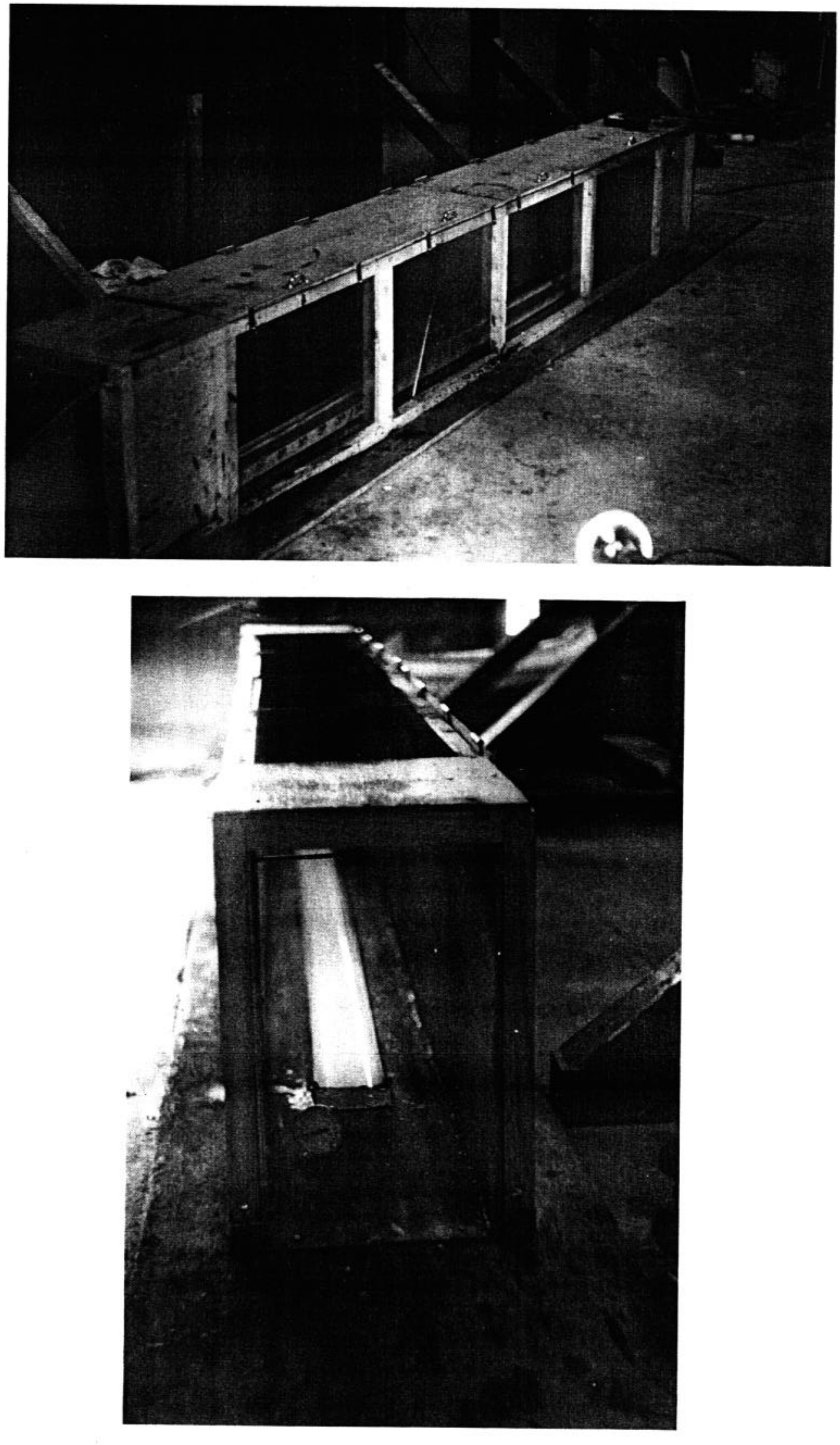


TABLE 1

OIL PHYSICAL PROPERTIES

PROPERTY	OIL TYPE			
	CRUDE AGED 1 HR.	CRUDE AGED 4 HRS.	CRUDE AGED 8 HRS.	FRESH DIESEL
DENSITY @ 15°C (g/cm^3)	0.850	0.857	0.865	0.844
VISCOSITY @ 15°C (cSt)	8.6	11.4	16.2	4.0
INTERFACIAL TENSION* @ 15°C (dynes/cm)				
OIL/AIR	26.7	26.8	27.6	28.4
OIL/WATER	21.7	21.9	22.0	28.1
INITIAL BOILING POINT (°C)	27	29	33	61

* WATER/AIR = 70.6 dynes/cm

about 50 m in diameter before extinguishing. Unfortunately, due to unusually dry spring weather, the selected test site did not fill with sufficient water to conduct the trials. As such, an alternative test plan, involving extensive air-entrainment measurements on larger diameter fires is to be conducted in Waterloo and possibly Ottawa. Air entrainment velocities will be recorded using specially designed pitot tubes, placed around containment rings of various diameters.

RESULTS AND DISCUSSION

Small-Scale Testing

Oil Spreading

Fay (1971) has developed the following equations to predict one dimensional spreading in the regieme where gravity forces predominate.

Gravity - Internal

$$(1)\ l = 1.5\ (\Delta\ g\ At^2)^{1/3}$$

Gravity - Viscous

$$(2)\ l = 1.5\ (\Delta\ gA^2\ t^{3/2} / \nu^{1/2})^{1/4}$$

where l = length of slick (cm)

Δ = ratio of density difference between water and oil to density of water

g = acceleration of gravity ($981\ cm/s^2$)

t = time since initiation of spread (s)

A = volume of oil per unit length normal to direction of spread (cm^2)

ν = kinematic viscosity of water ($10^{-2}\ cm^2/s$)

Figure 2 shows a plot of the oil spreading and Fay's prediction. Figure 3 shows the same results plotted in the non-dimensional form used by Fay. In both cases the data follows 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 acutal and predicted spreading increases.

FIGURE 2
OIL SPREADING
(No wind)

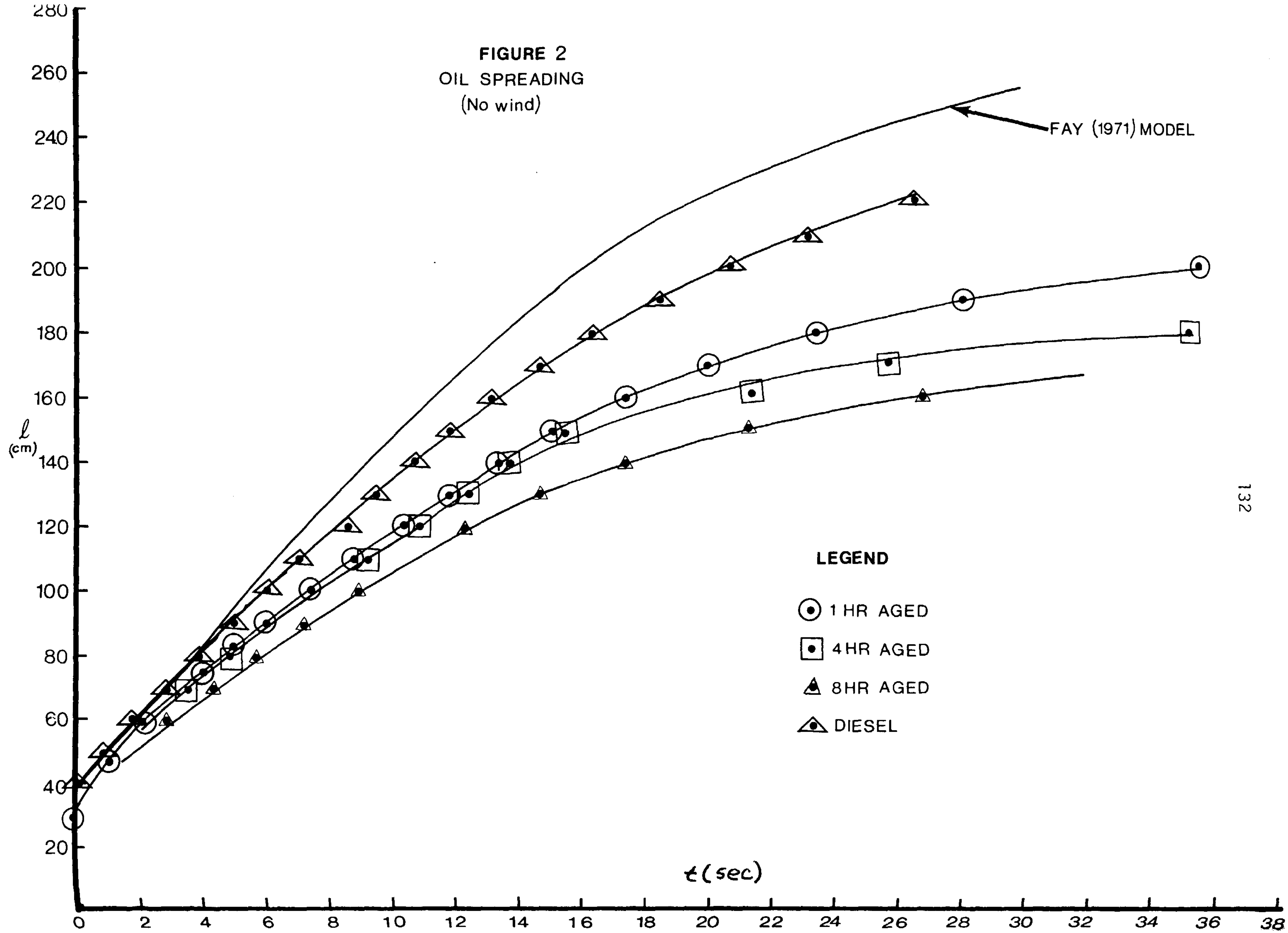
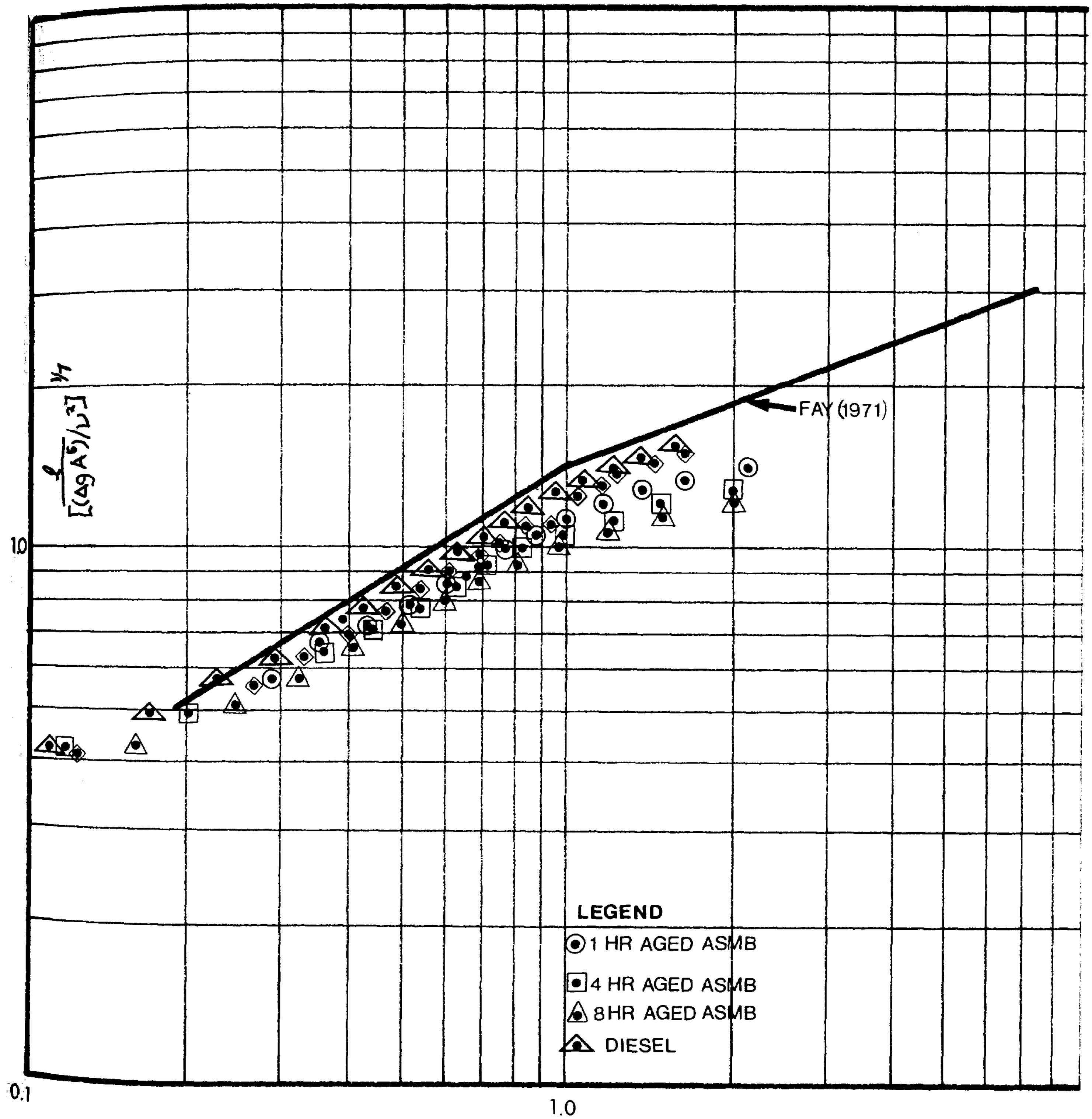


FIGURE 3

NON–DIMENSIONAL OIL SPREADING



$$\frac{t}{\left[\frac{A^4}{(\Delta g^2)\nu^3}\right]^{1/7}}$$

In order to attempt to quantify this phenomenon, plots of the ratio of actual to predicted spreading vs the ratio of the oil to water viscosity were prepared. These are shown in Figure 4 for both the gravity-inertia and gravity-viscous spreading regimes. It can be seen that the oil viscosity effect can be adequately described by an equation of the form:

(3) actual spread $= \left(\frac{\mu}{\mu_w}\right)^n$ predicted spread

where μ = dynamic viscosity of oil

μ_w = dynamic viscosity of water

n = a constant unique to each regieme

Thus, oil spreading in the gravity regiemes can be more accurately predicted by:

Gravity - Inertia

$$(4) \qquad l = 1.5\left(\frac{\mu}{\mu_w}\right)^{-0.09}(\Delta g A)^{1/3} t^{2/3}$$

Gravity - Viscous

$$(5) \qquad l = 1.5\left(\frac{\mu}{\mu_w}\right)^{-0.15}\left(\Delta g A^2/\nu^{1/2}\right)^{1/4} t^{3/8}$$

Oil Spreading with Wind

An aerodynamic analysis of the wind tunnel has resulted in the following conversion from a wind tunnel speed (measured 10 cm above the oil) to an atmospheric wind (measured 10 m above sea level)

(6) $V_{10} = 1.239\ V_{0.1}{}^{1.1275}$ m/s

where $V_{0.1}$ = wind tunnel velocity (m/s)
V_{10} = atmospheric wind velocity (m/s)

Figure 5 illustrates the data from a typical series of runs to investigate the effects of wind on oil spreading. The data points denoted as a run with a positive wind speed were obtained with the wind in the same direction as the oil spreading; those denoted as a run with a negative wind speed were obtained with the wind opposing the oil spreading.

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

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

where F_s = spreading force
ρ = water density
ρ_o = oil density
w = slick width
h = slick thickness

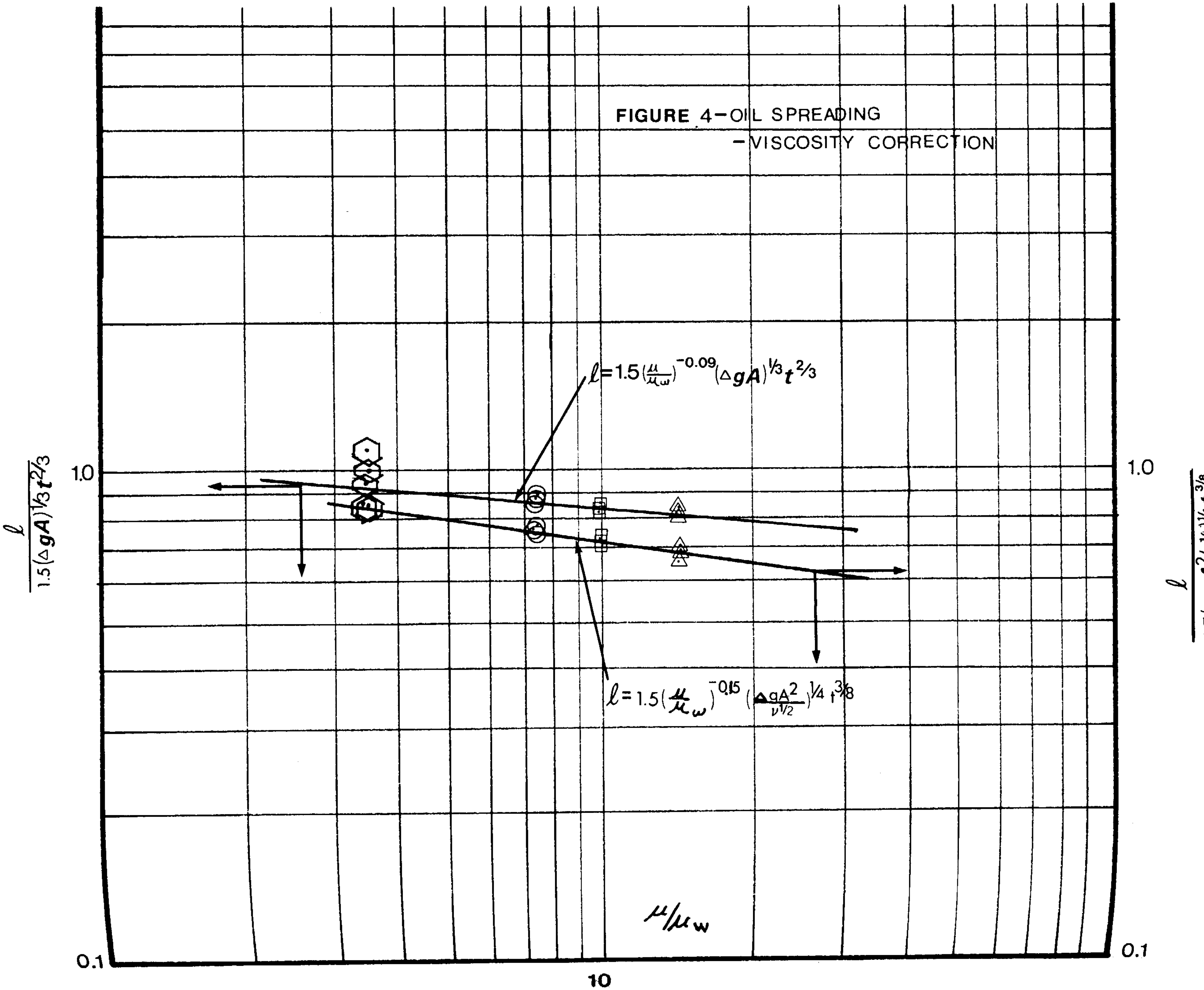


FIGURE 4—OIL SPREADING
—VISCOSITY CORRECTION

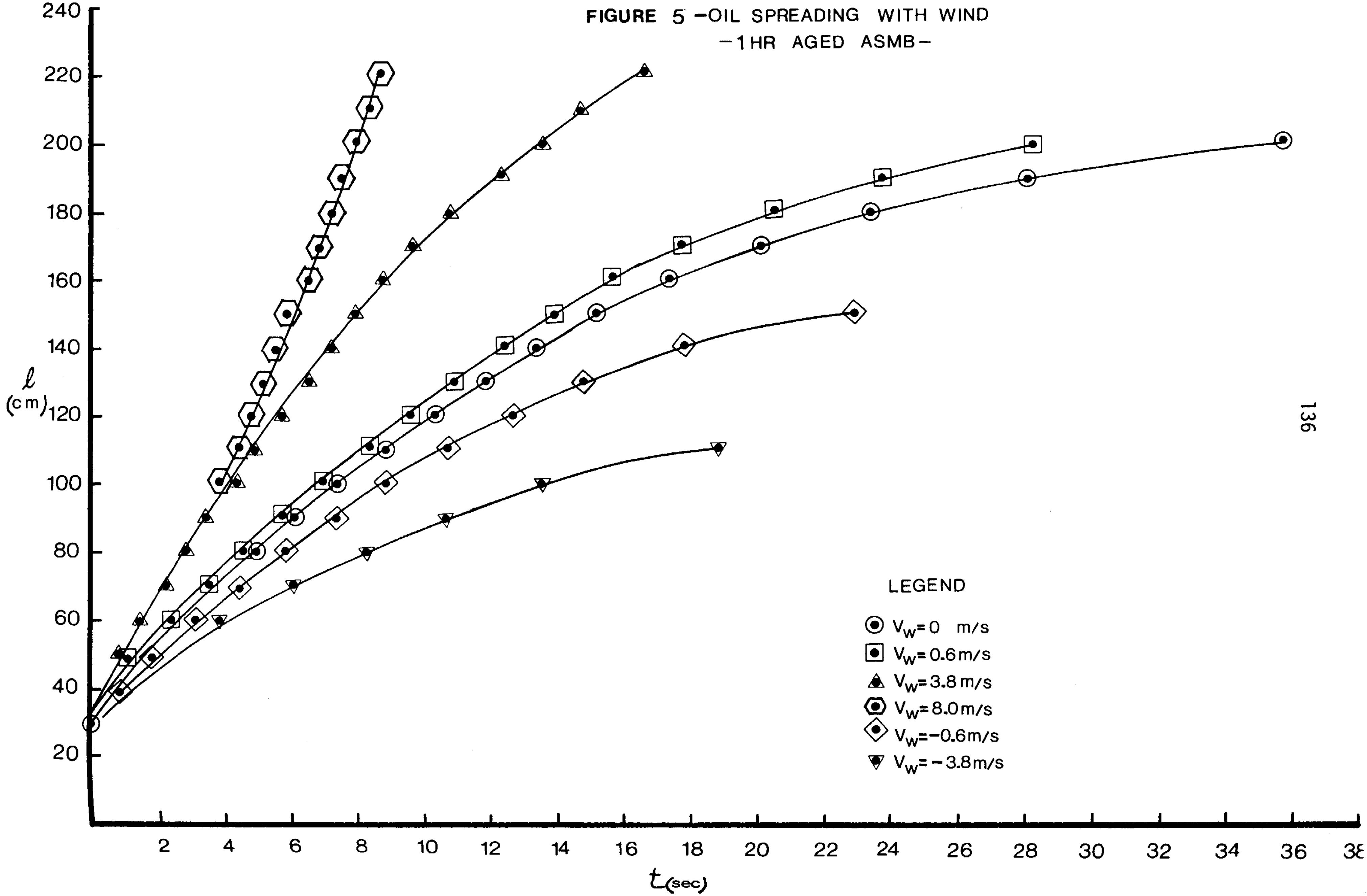


FIGURE 5 –OIL SPREADING WITH WIND
–1HR AGED ASMB–

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

(8) $F_W = C_D V \rho_A U^2/h$

where F_W = wind retarding face

C_D = drag coefficient of slick

V = slick volume

ρ_A = air density

U = wind velocity

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

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

or

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

which can be rewritten as

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

Figure 6 shows a plot of h^3/V vs U. A plot of equation 12 with $C_D = 3.5 \times 10^{-3}$ is also given. The equation fits the data quite well except as 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. Figure 7 compares the model (equation 12) with the experimental data.

Flame Spreading Over Oil

Figure 8 shows the length of the 3mm thick slick of 1 hour aged Alberta Sweet Mixed Blend on fire as a function of time for various wind speeds. 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 9 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 vapours) was measured at 1.3 m/s.

The results of these tests indicate that the data can be approximated by an equation of the form.

(11) $U_F = mU + b$ [m/s]

where U_F = flame velocity [m/s]

m ,b = constants

As well, it appears that both m and b are functions of oil type. In order to quantify the effect of oil type, the Initial Boiling Point (T_B) was selected to represent the volatility of the oil. Figure 10 shows the relationships between the slope (m) and intercept (b) of the data on Figure 9 and the Initial Boiling Point of the oil.

In order to model the data, the parameter:

(12) $\dfrac{T_B - T_A}{T_B}$ where T_A = ambient temperature (°K)

T_B = initial boiling point of oil (°K)

FIGURE 6– WIND DRAG COEFFICIENT DETERMINATION

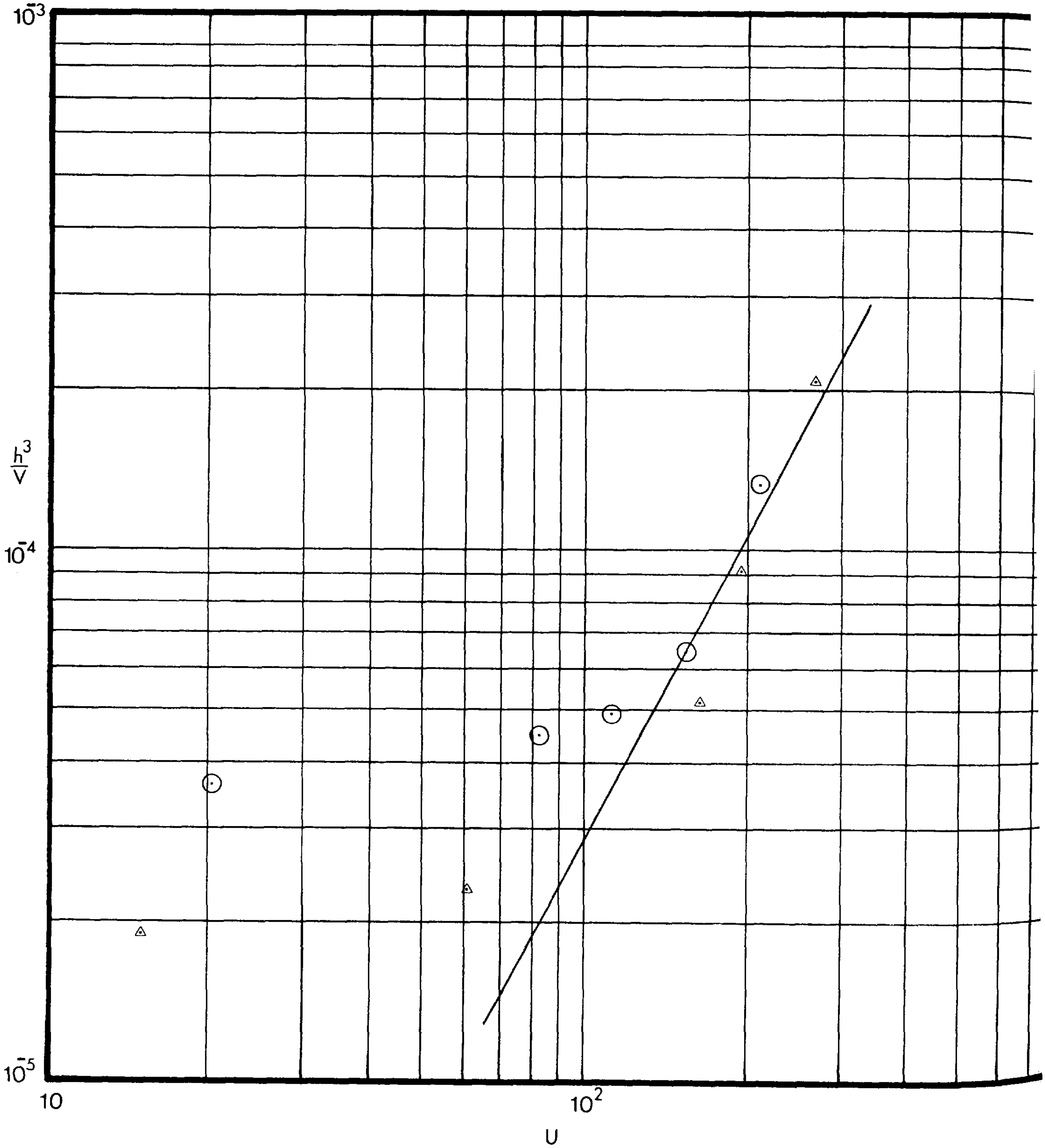
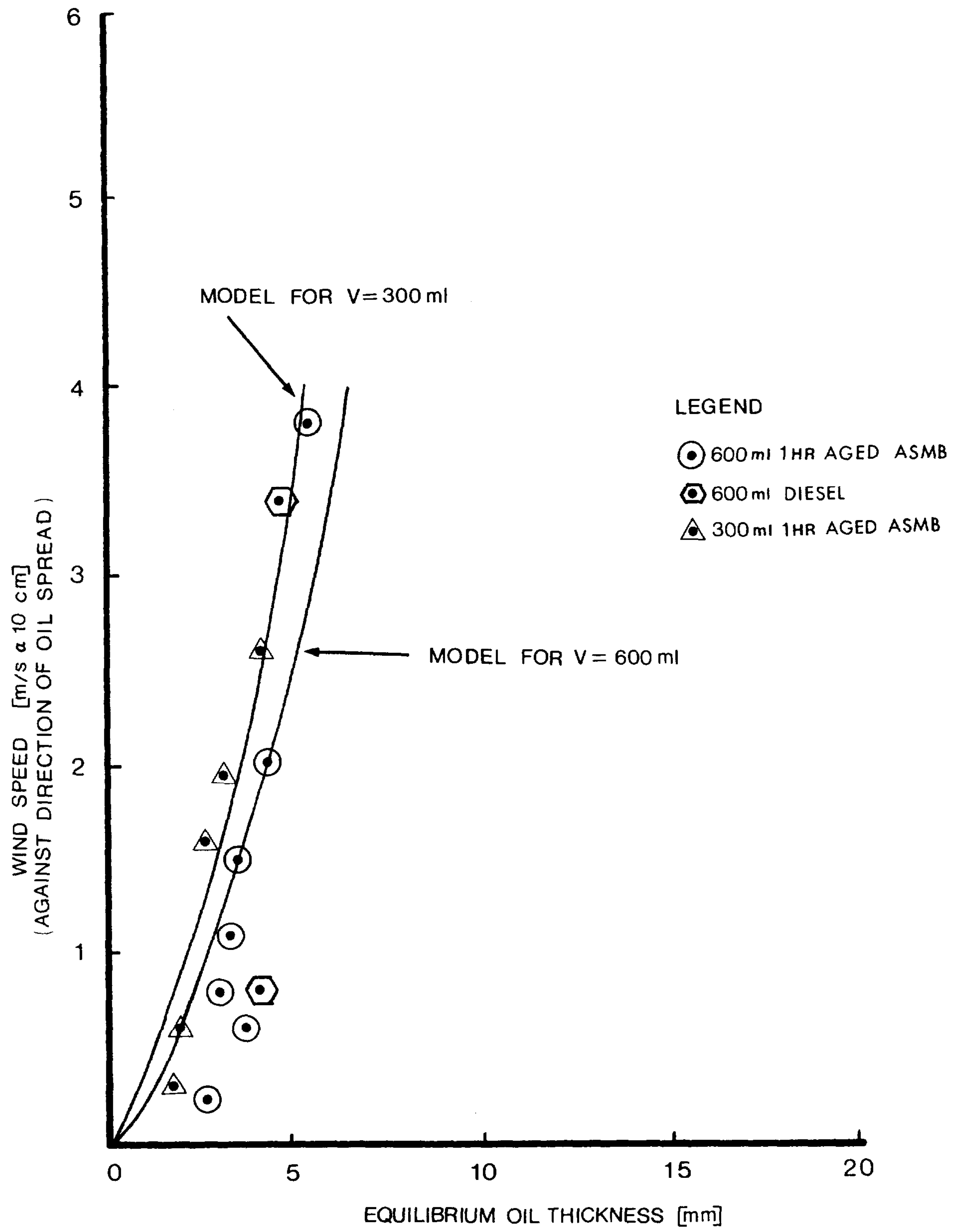


FIGURE 7

EQUILIBRIUM OIL THICKNESS
VS
OPPOSING WIND SPEED



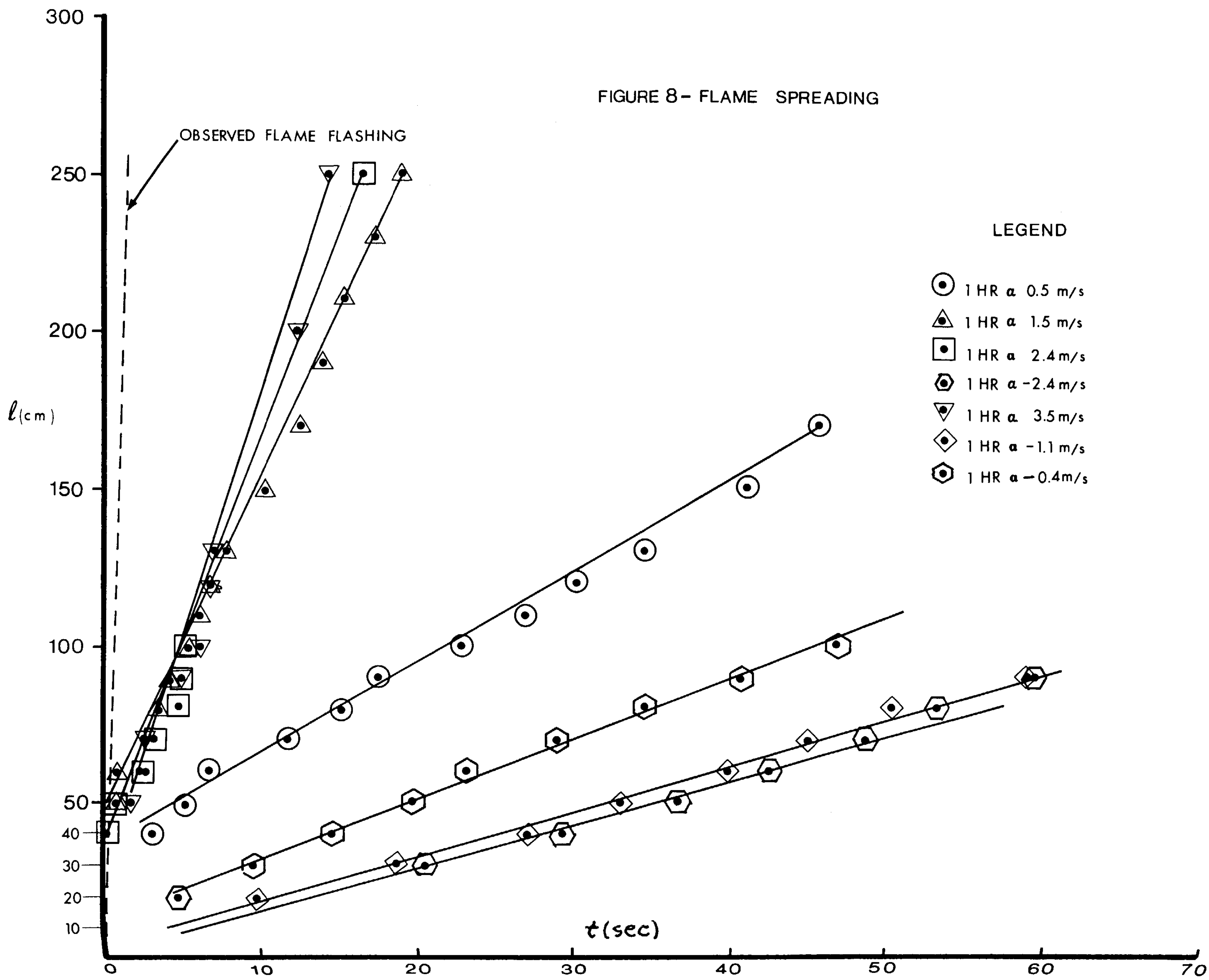


FIGURE 8 - FLAME SPREADING
OBSERVED FLAME FLASHING
LEGEND
1 HR a 0.5 m/s
1 HR a 1.5 m/s
1 HR a 2.4 m/s
1 HR a -2.4 m/s
1 HR a 3.5 m/s
1 HR a -1.1 m/s
1 HR a -0.4 m/s
ℓ (cm)
t (sec)
300
250
200
150
100
50
40
30
20
10
0
10
20
30
40
50
60
70

FIGURE 9 - FLAME SPEADING VELOCITY

NOTE - Flame flashing velocity measured at 1.3 m/s

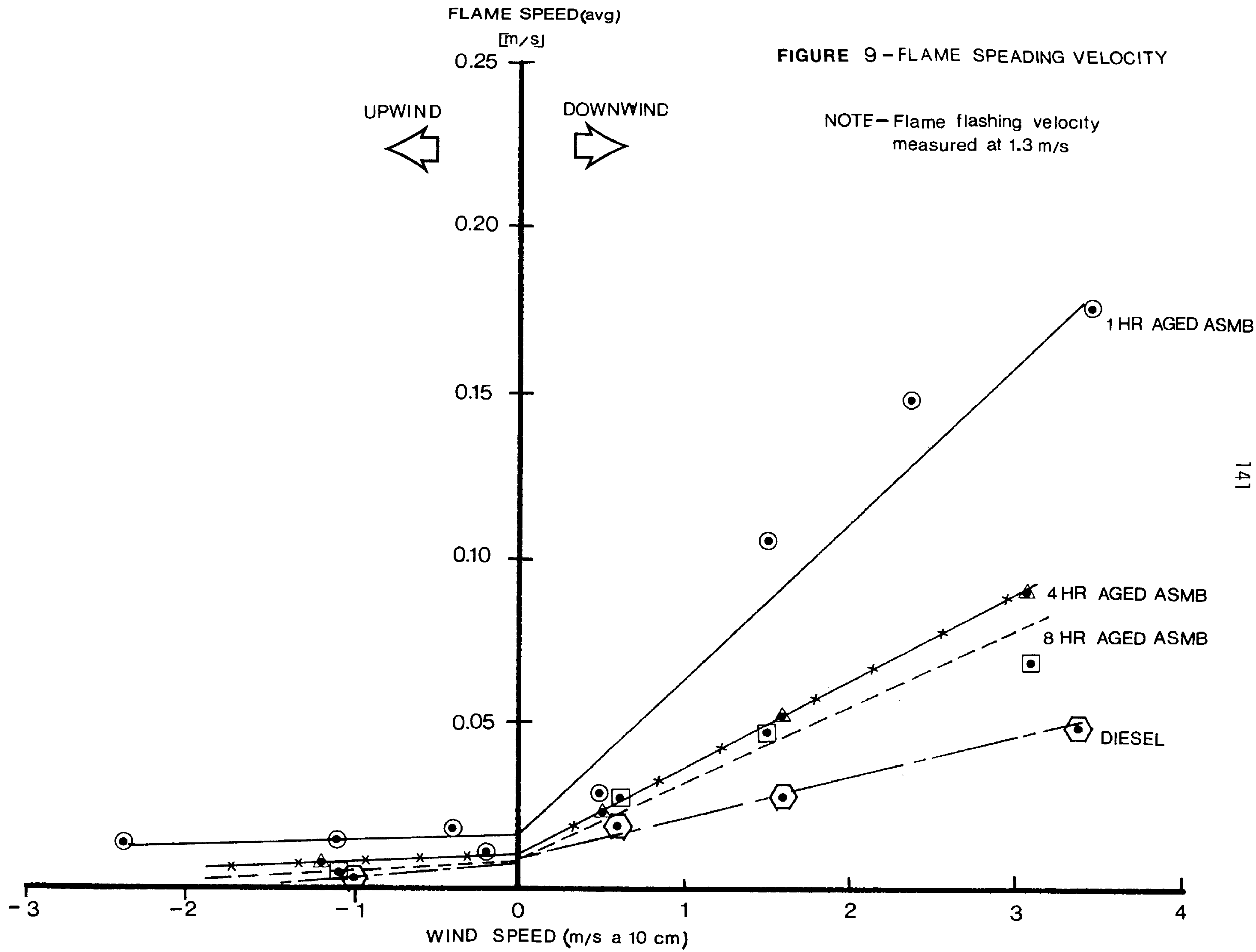
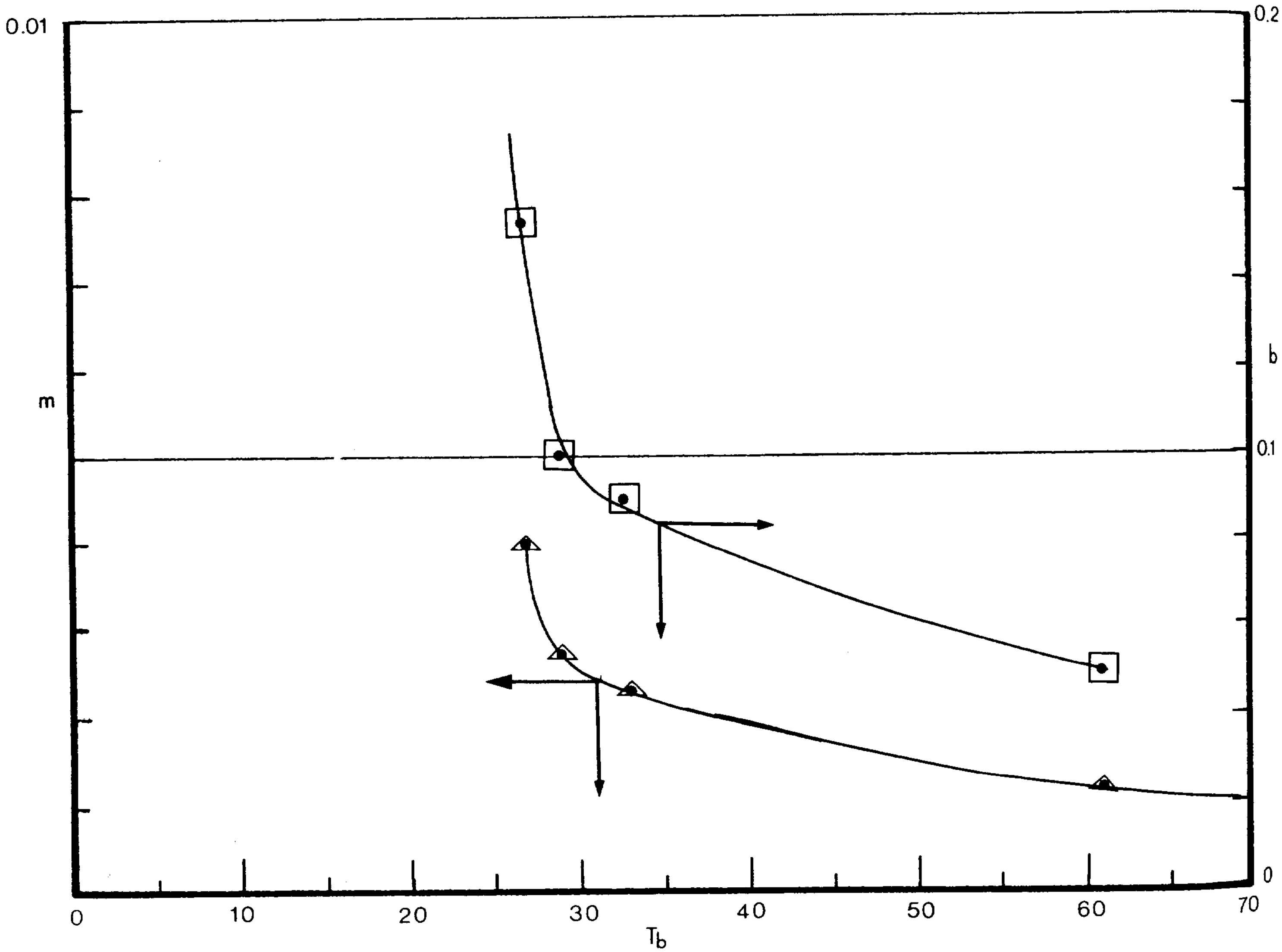


FIGURE 10

Dependence of m and b on Initial Boiling Point



was used. The model for b was determined to take the form:

$$(13) \qquad b = 1.3 \ \exp\left(-c\ (T_B - T_A/T_B)^d\right)$$

where c,d = constants

This equation has the properties that, as T_B increases, b decreases exponentially and when $T_B = T_A$, b is constant at 1.3 m/s (the flame flashing velocity with no wind).

The model for m was determined to take the form:

$$(14) \qquad m = \exp\ \left(-f\ (T_B - T_A/T_B)^g\right)$$

were f, g = constants

This equation also has the property that, as T_B increases, m decreases exponentially and when $T_B = T_A$, m is constant at 1 (the flame flashing velocity is equal to the wind speed plus 1.3 m/s).

Both the models for m and b have the property that as T_A increases m and b increase slightly. This is consistent with the data shown in Figure 11.

Figure 12 shows the fit of the experimental data points to equations 13 and 14 with:

c = 7.88
d = 0.1856
f = 6.52
g = 0.2302

Combining equations 11, 13 and 14 to give the overall equation for downwind flame spreading velocity as a function of wind speed yields:

$$(15) \qquad U_{F_d} = \exp\ (6.52\ (T_B - T_A/T_B)^{0.23})U + 1.3\ \exp\ (-7.88\ (T_B - T_A/T_B)^{0.19})$$

Although upwind flame spreading velocity is a weak function of wind speed (see Figure 9) for the purposes of this work it can be assumed to be independent of wind speed. Thus:

$$(16) \qquad U_{F_u} = 1.3\ \ \exp\ (-7.88\ (T_B - T_A/T_B)^{0.19})$$

Combined Oil and Flame Spreading

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

With all the crude oils tested the flame kept up with the oil spreading over the entire range of wind speeds tested. Figure 13 shows the typical results obtained for the 4 HR ASMB at a wind speed of 0.25 m/s. 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 only at wind speeds less than 1 m/s in the tunnel.

FIGURE 11
Flame Spreading
vs
Temperature

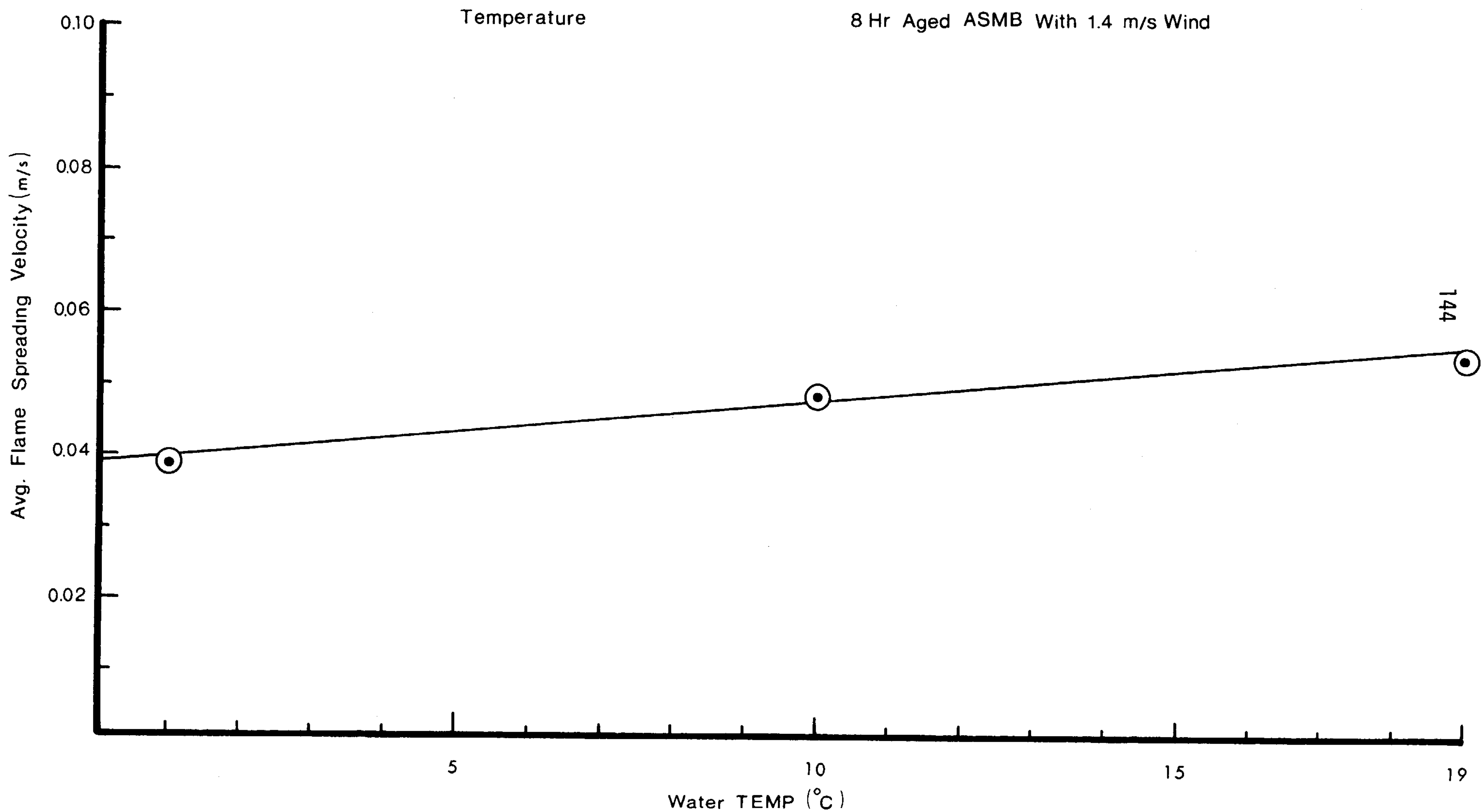
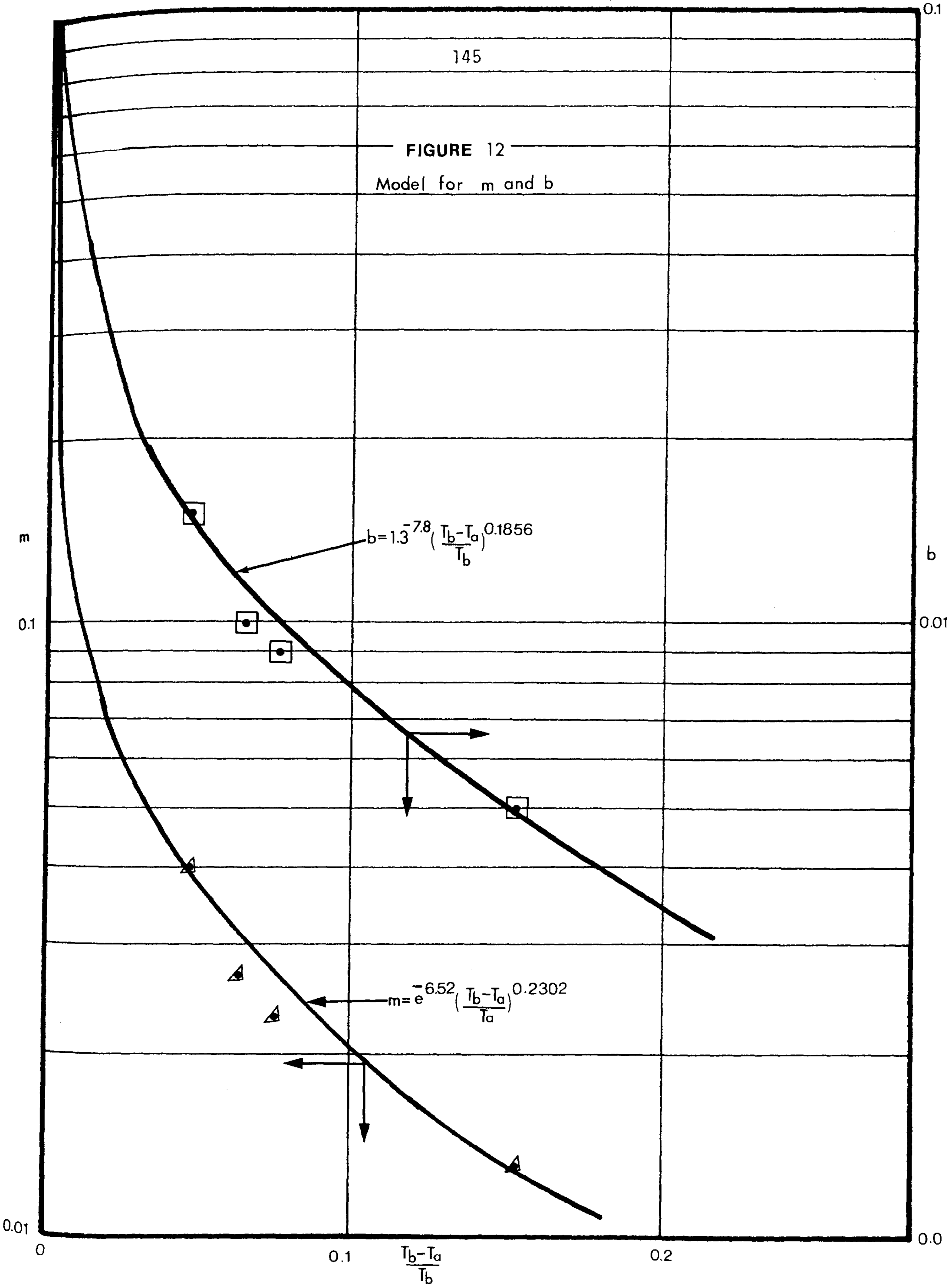


FIGURE 12

Model for m and b



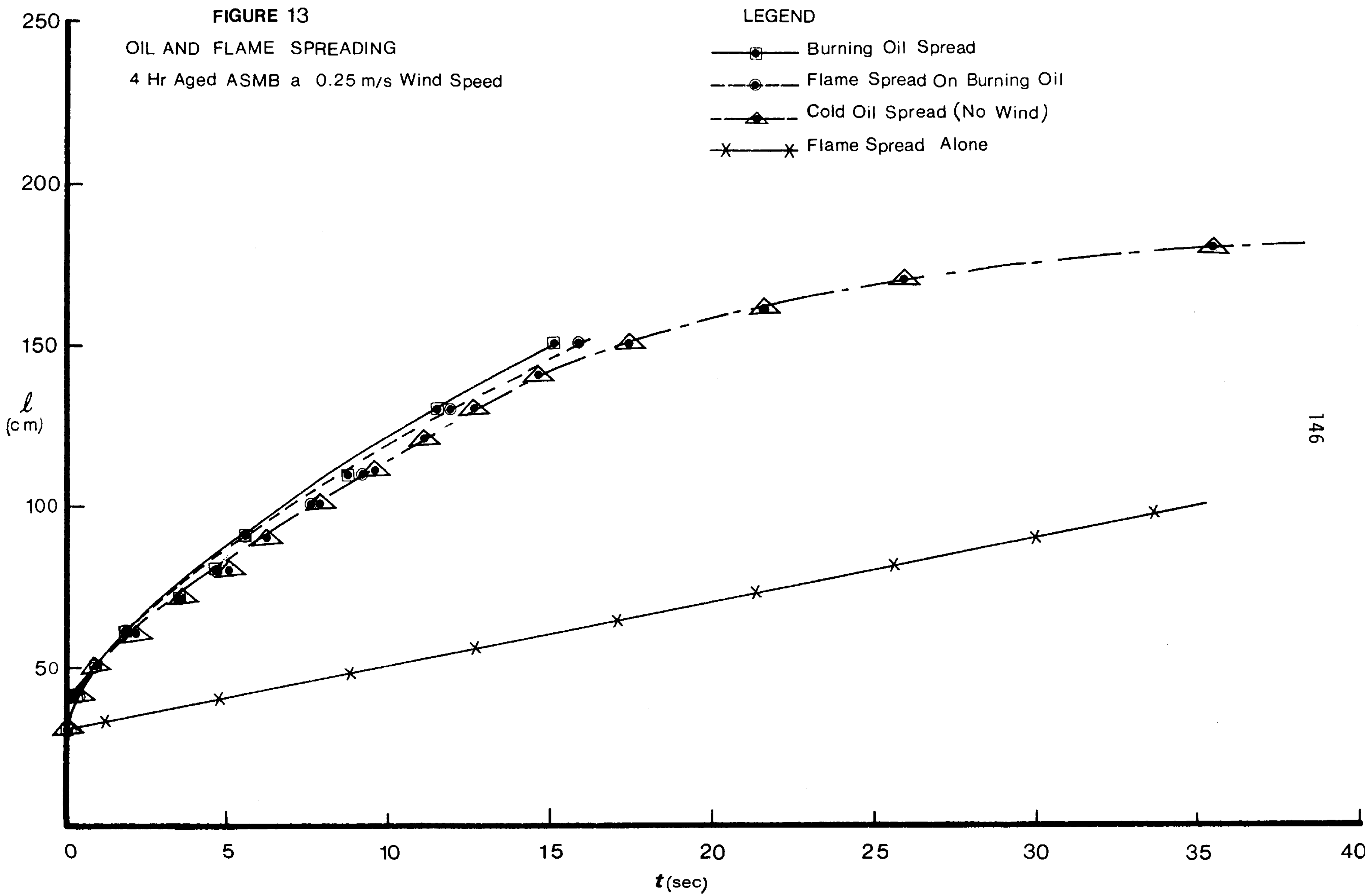


FIGURE 13
OIL AND FLAME SPREADING
4 Hr Aged ASMB a 0.25 m/s Wind Speed
LEGEND
Burning Oil Spread
Flame Spread On Burning Oil
Cold Oil Spread (No Wind)
Flame Spread Alone
ℓ (cm)
250
200
150
100
50
t (sec)
0
5
10
15
20
25
30
35
40

Mid-Scale Testing

Combustion Efficiency of Unconfined Slicks

For thick oil in the gravity-viscous spreading regime in calm water (Fay, 1971) the area of the slick can be approximated by:

17) $$A = 4.6\ V_o^{\ 2/3}\ t^{1/2}$$

where A = slick surface area [m^2]

V_o = initial oil volume [m^3]

t = time [s]

The volume of oil consumed by burning is the product of the area of the slick on fire, the length of time the slick has been on fire and the oil consumption rate.

If it is assumed that the entire volume of oil is released instantaneously, ignited at the same time and that the rate of flame spreading equals or exceeds the rate of oil spreading (i.e. the entire surface of the slick is always on fire) then the volume of oil burned is:

18) $$V_B = Z\ At$$

where V_B = volume of oil consumed by fire [m^3]

Z = oil consumption rate [m^3/m^2s]

Substituting equation 13 into 17 yields,

19) $$V_B = 4.6\ Z\ V_o^{\ 2/3}\ t^{3/2}$$

The slick thickness X at any given time is:

20) $$X = \frac{V_o - V_B}{A}$$

If it is further assumed that the oil consumption rate is constant until the slick thickness drops to 1 mm, at which time the fire extinguishes, the total burn time (t_B) can be calculated by substituting X = 0.001 m, equation 2 and equation 3 into equation 4 yielding:

21) $$t_b^{\ 3/2} + t_B^{\ 1/2}/10^3 Z = V_o^{1/3}/4.6Z$$

Table 2 shows the oil consumption rates measured as a function of the initial thickness of a 1 m diameter pool of oil. For slicks of this size thicker than about 2 cm the rate is constant at about 2 mm/min or 3.3 x 10^{-5} m^3/m^2s. This is consistent with the observations of others (eg. McAllister and Buist, 1981; Wakimaya et al, 1982)

Substituting this into Equation 21 yields:

22) $$t_B^{\ 3/2} + 30\ t_B^{1/2} = 6.6 \times 10^3\ V_o^{1/3}$$

Values of t_B are calculated for each volume then substituted into Equation 19 to determine the volume and percentage of the oil burned. Figure 14 shows the results of the combustion tests in comparison to the model.

The model consistently overestimates the actual results, probably due to the use of of an average consumption rate rather than a time-dependant one.

TABLE #2

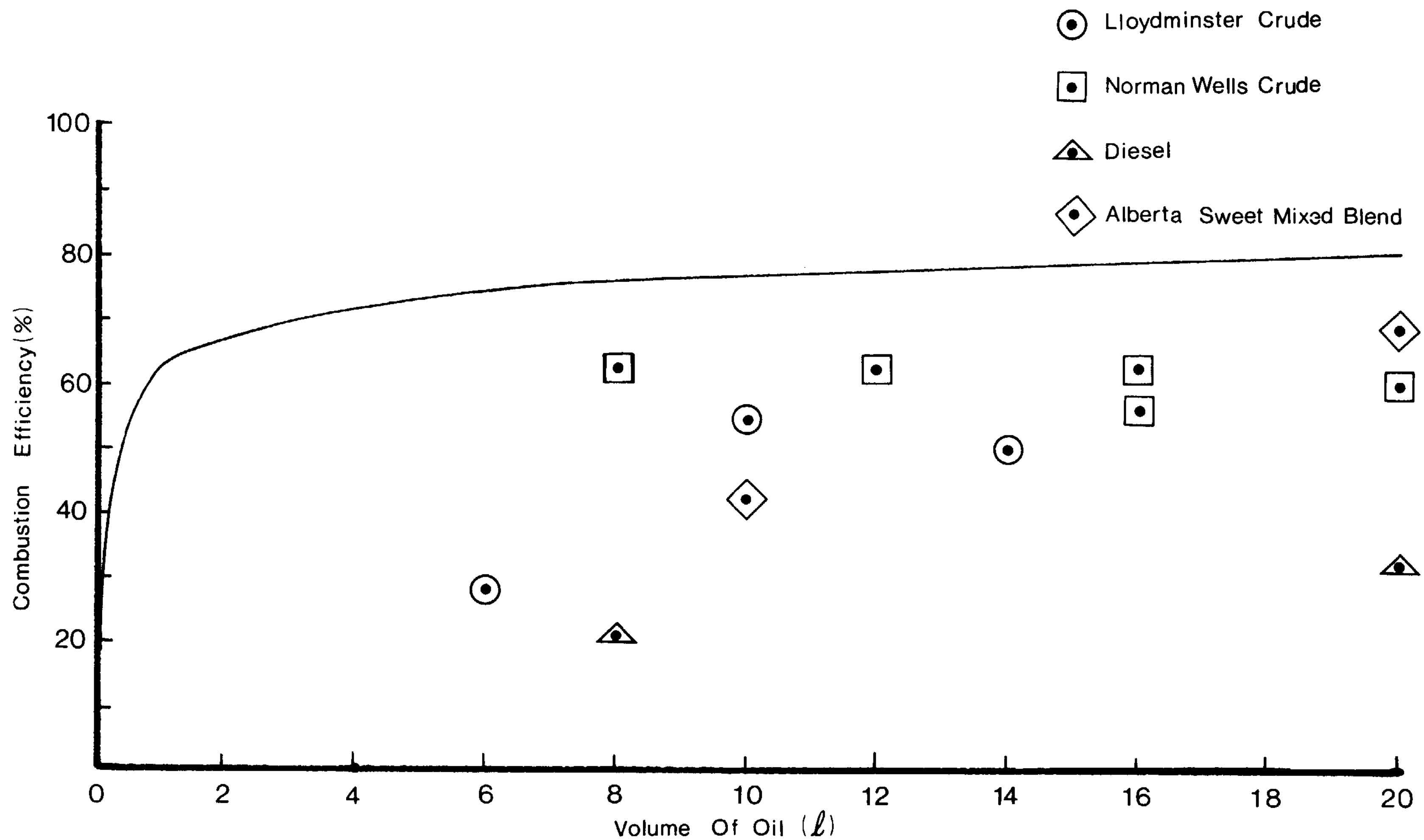
CONTAINED OIL SLICK - REGRESSION BURNING RESULTS

Test No.	Oil Type	Oil Volume (l)	Pool Dia. (m)	Initial Oil Thickness (mm)	Residue Volume (l)	Residue Thickness (mm)	Burning Time (min)	Regression Burning Rate (mm/min)
1	ASMB	4	1	5.0	0.7	0.9	2:20	1.8
2	ASMB	6	1	7.6	0.85	1.1	3:15	2.0
3	ASMB	8	1	10.1	0.95	1.2	4:50	1.84
4	ASMB	10	1	12.7	0.95	1.2	6:40	1.7
5	ASMB	12	1	15.3	1.0	1.27	8:35	1.65
6	ASMB	16	1	20.3	1.0	1.27	11:43	1.63
7	ASMB	16	1	20.3	0.8	1.0	9:30	2.0
8	ASMB	17	1	21.6	0.8	1.0	10:00	2.0
9	ASMB	20	1	25.47	1.0	1.27	14:00	1.72
10	ASMB	32	1	40.7	0.9	1.15	19:00	2.0
11	Diesel	6	1	7.6	1.1	1.4	3:50	1.6 *
12	Diesel	12	1	15.3	1.6	2.0	7:15	1.8 *
13	Diesel	20	1	25.47	0.9	1.15	11:50	2.0
14	Diesel	12	2	3.8	4.2	1.33	2:20	1.0 *
15	Diesel	20	2	6.36	4.1	1.3	3:00	1.68 *
16	ASMB	10	2	3.18	1.7	0.54	1:35	1.74
17	ASMB	14.7	2	4.67	2.3	0.73	2:00	1.97
18	ASMB	20	2	6.36	2.7	0.859	2:19	2.39

* Residue emulsified

FIGURE 14

COMPARISON OF EXPERIMENTAL
COMBUSTION RESULTS WITH THEORY



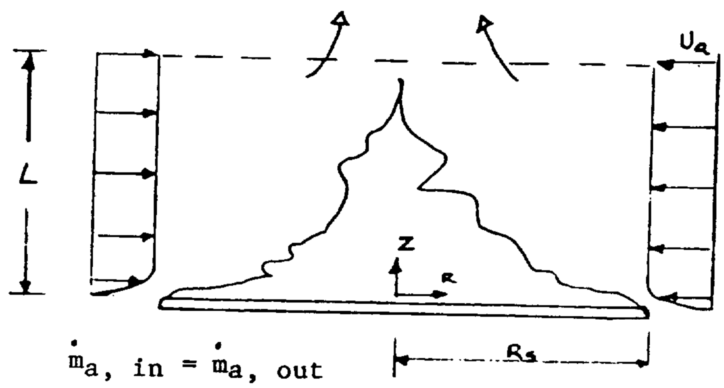
The trends in unconfined slick combustion efficiency are, however, adequately described by the model. It should be reiterated that these results are based on the release and spread of already burning oil; delays in slick ignition will reduce the possible combustion efficiency.

Oil and Flame Spreading

In all the tests observed so far with crude oils the flame spread with crude oils the flame spread as rapidly as the burning oil until the thickness of the leading edge of the slick dropped below that necessary to support combustion. After this point only the thick portions of the slick were burning. The fire went out when the entire slick thinned to less than about 1 mm.

AIR ENTRAINMENT AND PROPOSED LARGE-SCALE TESTING

Assuming a single flame of length L,a mass balance on air alone gives



(23) $$\dot{m}_{a,\,in} = \dot{m}_{a,\,out}$$

but

$$\dot{m}_{a,\,in} = 2\pi r_s \rho_a \int_0^L u(z)dz$$

(24) $$= 2\pi r_s \rho_a L u_a$$

if the displacement thickness of the air boundary layer is ignored. The air outflow can be related to the burning rate

(25) $$\dot{m}_{a,out} = (a/f)_{st} \cdot \psi \cdot \dot{m}_f$$

where $(a/f)_{st}$ is the stoichiometric air/fuel ratio by weight $\sim$15 for h/c, ψ is the dilution factor, -5 for diffusion flames of h/c,

(26) $$\therefore \quad \dot{m}_{a,out} \doteq 75\dot{m}_f$$

For a small slick, the flame length is proportional to the slick diameter:

(27) $$L = \alpha r_s$$

The factor α is available in the literature (e.g. Becker and Liang, 1978).

Combining equations 23, 24, 26 and 27 gives

(28) $$2\pi r^2 \alpha \rho_a u_a = 75 \dot{m}_f$$

According to the NBS (Babrauskas, 1983) the burning rate m_f is proportional to the pool (or slick) area

(29) $$\dot{m}_f = \pi r^2 . \dot{m}_f''$$

where

(30) $$\dot{m}_f'' = \dot{m}_\infty'' (1 - e^{-2k\beta' r_s})$$

in which $\dot{m}_\infty''$, k, and β' are tabulated parameters which depend only on the fuel type. Combining 28, 29, and 30 gives

$$2\pi r^2 \alpha \rho_a u_a = 75\pi r^2 \dot{m}_\infty'' (1 - e^{-2k\beta' r_s})$$

from which

(31) $$u_a = \frac{37.5\, \dot{m}_\infty''(1 - e^{-2k\beta' r_s})}{\alpha\, \rho_a}$$

Babrauskas gives $k\beta' = 2.8\ m^{-1}$ for crude oil, which means that for pools greater than 1 m in radius the exponential term in (31) is negligible, and

(32) $$u_a = \frac{37.5\ \dot{m}_\infty''}{\alpha\ \rho_a}$$

For crude oil $\dot{m}_\infty'' = 0.022$ to $0.045\ kg/m^2s$. Take 0.033 as a typical value. With $\rho_a = 1.28\ kg/m^3$

(33) $$u_a = \frac{37.5 \times 0.033}{\alpha \times 1.28} = \frac{1}{\alpha}\ m/s$$

1.2 <u>For a large slick,</u> the flame length is no longer proportional to r_s. Becker and Liang give the relation

(34) $$L = 12 \frac{\beta^2 (\dot{m}_\infty'')^2}{g \rho_a^2 W_1^2}$$

Evaluating the constants for a typical hydrocarbon leads to the following working equation

(35) $$L = 1.47 \times 10^3 (\dot{m}_\infty'')^2 = \text{const}$$

With $\dot{m}'' = \dot{m}_\infty''$ at 0.033, L = 1.6 m. With flames as short as this and spread over a wide area, the value Ψ = 5 may be a bit uncertain. However, the data from which this value was drawn did include some relatively large fires of several metres in radius. Therefore, until better data is experimentally determined becomes available $\psi = 5$ will be used.

Equation 27 will now be replaced with (35). Combining this with (23), (24), (25) and (29) gives

(36) $$u_a = 37.5 \frac{r_s \dot{m}''}{L \rho_a}$$

With L = 1.6 m, $\dot{m}'' = 0.033$ kg/m^{2}s, $\rho_a = 1.28$ kg/m^3

(37) $$u_a = 0.6 r_s$$

Thus, there are two possible expressions for Ua; one in which it is a constant (the constant being inversely related to the constant ratio of fire height to slick radius) and one in which it is related to the radius of the slick on fire.

Using the latter, Fay's expression for gravity spreading force for a circular spill, the wind drag force equation determined from the wind tunnel experiments and assuming that the entrained wind acts only over the outer 10% of the burning slick radius, it can be shown that the equilibrium slick thickness is given by:

(38) $$h_e = 0.6 \left(\frac{0.2 C_d \rho_a}{(\rho - \rho_o) g}\right)^{1/2} r^{3/2}$$

substituting $C_d = 3.5 \times 10^{-3}$, $\rho_a = 1.28$ kg/m^3, $(\rho - \rho_o) = 150$ kg/m^3 and $g = 9.8$ m/s^2

(39) $$h_e = 4.6 \times 10^{-4} r^{3/2}$$

For the case where Ua is independant of r, and assuming $\alpha = 1$ (ie. the flame height equals the slick radius):

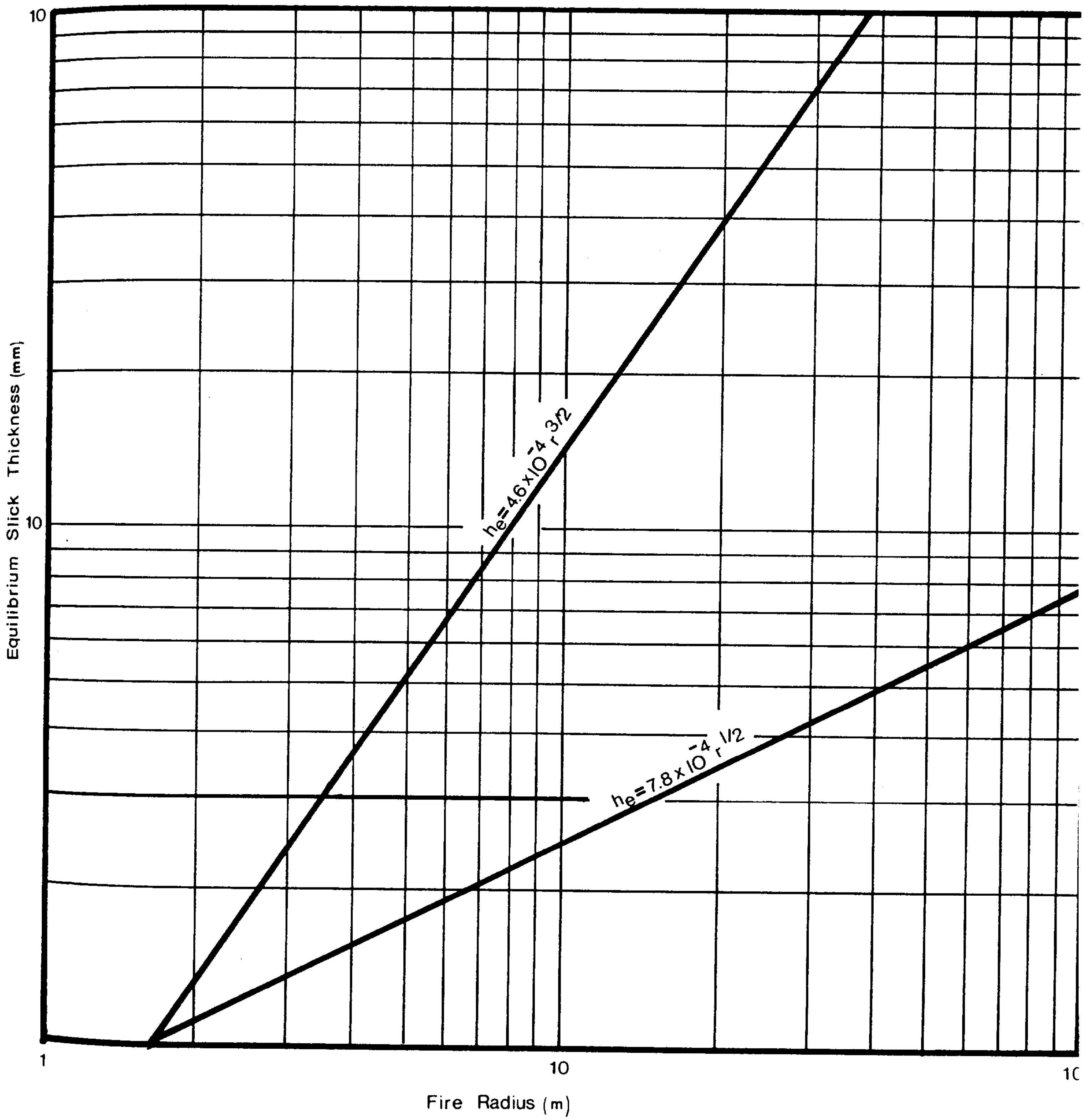
(40) $$h_e = 7.8 \times 10^{-4} r^{1/2}$$

Comparison of these two models is shown on Figure 15. For those slick radii with equilibrium slick thicknesses in excess of 2 mm, effecient uncontained combustion is possible.

There are two major uncertainties in these models, namely, the relationship between fire radius and entrained air velocity, and what fraction of the retarding force of the wind acts on the slick. These factors are being addressed in the revised third phase of the study experiments.

A model is also being developed to predict the time dependent behaviour of a slick. It combines slick spreading, induced air flow, combustion rate, flame spreading and ignition delay.

FIGURE 15
Equilibrium Thickness of a Burning Oil Slick



SUMMARY

To date experiments have been conducted to determine and model the relationships between oil type, oil spreading, flame spreading and combustion efficiency. Further testing is underway to quantify entrained air velocities near the edge of a burning slick. A computerized model is being developed to combine a variety of models and permit prediction of uncontained oil slick combustion efficiencies.

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