Environment Canada · Environnement Canada

Canada Centre For Inland Waters · Centre Canadien Des Eaux Intérieures

USE OF BOOMS FOR OIL SLICK CONTROL

by

Y. L. Lau and J. Moir

UNPUBLISHED REPORT
RAPPORT NON PUBLIE

Lau (27)
Moir (2)

This manuscript has been submitted to the Journal of the Hydraulics Division, ASCE, for publication and the contents are subject to change.

This copy is to provide information prior to publication.

USE OF BOOMS FOR OIL SLICK CONTROL

by

Y. L. Lau and J. Moir

Environmental Hydraulics Section
Hydraulics Research Division
Canada Centre for Inland Waters
April 1978

TABLE OF CONTENTS

FOREWORD: MANAGEMENT PERSPECTIVE

ABSTRACT

		Page
1.0	INTRODUCTION	1
2.0	ANALYTICAL CONSIDERATIONS	3
	2.1 Frontal Zone	3
	2.2 Viscous Zone	3
	2.3 Diversion of Oil Slicks	5
3.0	EXPERIMENTS	7
	3.1 Failure Criteria	7
	3.2 Slick Profile and Interfacial Friction	7
	3.3 Diversion	8
4.0	RESULTS AND DISCUSSION	9
	4.1 Failure Criteria	9
	4.2 Interfacial Friction Factor	11
	4.3 Diversion	13
5.0	SUMMARY	15

APPENDIX I - REFERENCES

APPENDIX II - NOTATION

FOREWORD: MANAGEMENT PERSPECTIVE

This report provides additional design criteria for booms which are to be deployed in flowing water to control or collect spilled oil.

The first part of the paper provides a new criteria for the minimum depth of the boom to retain the oil. Previous criteria for static equilibrium conditions are shown to be insufficient. The results are therefore useful for the selection of locations to place a given boom or to design a boom for specific conditions. The second part of the paper shows the maximum angles to the current at which booms should be placed in order to ensure that the oil slick will be diverted. This latter criteria also provides a method to select suitable places for oil boom placement.

T. M. Dick
Chief
Hydraulics Research Division
National Water Research Institute

AVANT-PROPOS: PERSPECTIVE - GESTION

Le présent rapport fournit des critères supplémentaires de conception d'estacades que l'on doit déployer dans des eaux courantes pour contenir ou recueillir une nappe de pétrole.

La première partie de l'étude comporte un nouveau critère touchant la profondeur minimale de l'estacade pour permettre à celle-ci de contenir le pétrole. Il y est démontré que les critères précédents touchant les conditions d'équlibre statique étaient insuffisants. Les résultats s'avèrent donc utiles pour déterminer les emplacements d'une estacade donnée ou pour concevoir une estacade convenant à des conditions précises. La seconde partie de l'étude indique l'angle maximal que doit faire une estacade avec le courant en vue d'assurer la déviation de la nappe de pétrole. Le dernier critère fournit aussi une méthode de détermination d'emplacements convenables pour les estacades.

T. M. Dick
Chef
Division de la Recherche hydraulique
L'Institute national de Recherce dans le
Domaine des eaux

ABSTRACT

Experiments were conducted to determine the conditions for no containment of oil by a boom, the oil-water interfacial friction coefficient and the maximum angle which a boom can be angled to the flow to deflect an oil slick. The criterion that the densimetric Froude number has to be smaller than about 5 for containment was verified. In addition, a new criterion was discovered which specifies a minimum boom draught. The local value of the interfacial friction coefficient was evaluated along the slick; using measured slick profiles, and was found to decrease along the length of a slick. The friction coefficient also increased with increasing oil viscosity. Based on the experimental results, an empirical relationship was derived for the maximum angle at which a barrier could be angled to the flow to completely divert an oil slick.

RÉSUMÉ

Des expériences ont été faites pour déterminer les conditions qui empêchent une estacade de retenir le pétrole, le coefficient de frottement des interfaces et l'angle maximal auquel peut être placée une estacade pour dévier une nappe de pétrole. Le critère voulant que le nombre densimétrique de Froude soit inférieur à environs 5, pour que l'on puisse contenir le pétrole, a été vérifié. En outre, un autre critere, qui détermine un tirant d'eau minimal pour l'estacade, a été découvert. La valeur locale du coefficient de frottement des interfaces a été évalée le long de la nappe de pétrole, à l'aide des profils de celle-ci, et il a été constaté qu'elle diminuait le long d'une nappe de pétrole. Le coefficient de friction était en rapport direct avec la viscosité du pétrole. Une relation empirique, fondée sur les résultats des expériences, a permis de déterminer l'angle maximal auquel une estacade pourrait être placée pour dévier complètement une nappe de pétrole.

1.0 INTRODUCTION

The dynamics of the containment of oil slicks in a current has been examined in depth by Wilkinson (9, 10). It was shown that dynamic forces dominated the frontal region of a slick and that there was a critical densimetric Froude number above which oil containment was impossible (9). The critical densimetric Froude number depended upon oil density as well as the flow depth and velocity upstream of the slick. For most oils the critical number was about 0.5. For the region downstream of the slick front, Wilkinson showed that viscous shear as well as dynamic forces affected the growth of the slick (10). However, the maximum possible thickness of a slick was also governed by the upstream densimetric Froude number only. An equation describing the form of a slick was derived. Given the upstream flow conditions, the oil density, the friction coefficient on the channel bottom and the friction coefficient at the oil-water interface, the equation could be integrated numerically to obtain the shape and length of the slick. The information was then used to compute the maximum volume of oil containable by a boom.

It should be pointed out that for practical situations the maximum slick as given by Wilkinson can seldom be realized. The maximum slick thickness is at least about 0.4 times the flow depth. However, most commercial booms which can be used in currents range in draught from about 15 centimetres to a metre (8). For a river of say, 6 metres depth, the maximum ratio of boom draught to flow depth is only about 0-16. Therefore, except for very shallow streams, oil will flow under the boom before the maximum thickness is reached and the volume of oil containable will be less than that given by Wilkinson. The effects of boom draught on containment has not been investigated.

To calculate slick profile and volume, the value of the interfacial friction coefficient, f_i, has to be known. Information on oil-water interfacial friction coefficient is very scarce. Cross and Hoult (2) reported f_i values for two slicks. Wilkinson (10) estimated values of f_i from the slopes of the interface but the values obtained were much smaller than those given by Cross & Hoult and are rather suspect. In the previous studies, it was assumed that f_i was constant when in fact it varied along the length of the slick. It is not known how much of an effect this assumption has on the profile of a slick.

In the present investigation, a large number of experiments were carried out to test the criterion for no containment. Boom draught was included as a parameter and in the process a new criterion for failure was discovered. Slick profiles were also measured in order to calculate the interfacial friction coefficient and to investigate the variation of f_i along the slick. The effect of oil property on f_i was also studied.

In situations where containment of oil was not possible, booms had been used to deflect oil slicks into areas where conditions were more favourable for collection. There is no information available as to when this is feasible and what angle the boom can be placed to the flow. A series of experiments has been made to produce some guidelines for deflection of oil slicks in a current.

2.0 ANALYTICAL CONSIDERATIONS

2.1 Frontal Zone

At the frontal part of a slick, viscous forces can be neglected in comparison with dynamic forces. Assuming steady, uniform flow, the one-dimensional momentum equation can be applied between the two sections upstream of and across the slick, as shown in Figure 1. From this momentum-pressure balance in the water layer, Wilkinson (9) derived the following equation relating the thickness of the slick front to the densimetric froude number:

$$F^2 = \phi\,(2-\phi)\left[\frac{2\phi}{1-\phi} + \frac{1}{1-\Delta}\right]^{-1} \qquad (1)$$

in which

$$\phi = h_o/d_o$$

$$\Delta = 1-\rho_o/\rho$$

$$F = U_o/(g\,\Delta d_o)^{1/2}$$

and h_o=thickness of the front of the slick; d_o=flow depth upstream of the slick; ρ_o=density of the oil; ρ=density of the water; U_o=velocity of flow upstream of the slick; and g=acceleration due to gravity.

Solutions of equation (1) show that Δ has very little effect on the relationship between F and ϕ. For $\Delta \to 0.0$, no solution exists when the densimetric Froude number F is greater than 0.527. Wilkinson suggested that when F>0.527, no stable slick could exist and that containment of oil by a barrier would be impossible. For values of F lower than this critical value, equation (1) gives the thickness of a slick at the front.

2.2 Viscous Zone

Downstream of the frontal zone, the slick thickens due to viscous shear at the oil-water interface. The equilibrium of the oil-water system depends on the balance of inertial and pressure forces against boundary shear. Assuming steady, uniform flow and negligible momentum due to the circulation in the oil, Wilkinson derived the following two equations (10).

For the whole oil-water system

$$\frac{\partial}{\partial x}\left[\rho g\,(1-\Delta)\frac{d^2}{2} + \Delta\rho g\,\frac{(d-h)^2}{2} + \frac{\rho\, U_o\, d_o^2}{d-h}\right] = -\tau_b \qquad (2)$$

For equilibrium of the oil-layer alone

$$\frac{\partial}{\partial x}\left(\frac{\rho_o g h^2}{2}\right) = \tau_i - \rho_o g h \frac{\partial}{\partial x}(d-h) \qquad (3)$$

in which x=length dimension in the flow direction; d=total depth at any section; h=thickness of oil layer; τ_b=shear stress at the bottom boundary; and τ_i=shear stress at the oil-water interface.

The shear stress terms were defined in terms of dimensionless friction coefficients, i.e.

$$\tau_b = \frac{f_b}{4}\rho\frac{u^2}{2} \qquad (4)$$

and

$$\tau_i = \frac{f_i}{4}\rho\frac{u^2}{2} \qquad (5)$$

in which f_b and f_i = boundary and interfacial friction coefficients respectively; and u = flow velocity at any given section.

Introducing equations (4) and (5) and non-dimensionalizing the length terms, equations (2) and (3) were rearranged into the following two equations:

$$\frac{\partial D}{\partial X}\left[\frac{D}{\Delta} - H - \left(\frac{F}{D-H}\right)^2\right] - \frac{\partial H}{\partial X}\left[D - H - \left(\frac{F}{D-H}\right)^2\right] = \frac{-f_b}{8}\left(\frac{F}{D-H}\right)^2 \qquad (6)$$

and

$$8H\frac{\partial H}{\partial X}\left\{D - \left[H + \left(\frac{F}{D-H}\right)^2\right]\right\} = \left(\frac{F}{D-H}\right)^2\left[\frac{f_i}{1-\Delta}\left\{D - \Delta\left[H + \left(\frac{F}{D-H}\right)^2\right]\right\} + f_b H\right] \qquad (7)$$

in which $X = x/d_o$; $D = d/d_o$; and $H = h/d_o$.

From numerical integration of equations (6) and (7), Wilkinson found that the value of D was always near unity. Taking D to be equal to 1.0, it can be seen that the bracketed term on the left hand side of equation (7) goes to zero when $H=(1-F^{2/3})$. For this value of H, $\partial H/\partial X$ becomes infinite. Thus, when the oil slick reaches this thickness, equilibrium can no longer be maintained and oil will flow under the barrier. This condition suggests that the maximum slick thickness, H_m is given by

$$H_m = 1 - F^{2/3} \quad (8)$$

As pointed out by Maxwell (5) this maximum slick thickness is the same as the maximum thickness of an arrested thermal wedge derived by Bata (1). In fact, if one assumes that $\Delta \to 0.0$ and $D \to 1.0$, Wilkinson's analysis is the same as Bata's for arrested thermal wedges.

For a flow with F equal to 0.25, equation (8) shows that the maximum slick thickness is 0.60 times the flow depth. For F equal to 0.45, the maximum thickness is 0.41 times the flow depth. As noted in the introduction, these maximum thicknesses cannot be attained except in some very shallow streams because of the limited draught of most oil booms. In practice, it is most likely that the boom draught will limit the maximum thickness of an oil slick. Using the maximum thickness as the boundary condition and given f_i, f_b, F and Δ, equation (7) can be integrated in the upstream direction to produce the profile and the volume of the slick.

2.3 Diversion of Oil Slicks

When conditions do not permit the containment of a slick, oil booms can still be deployed at an angle to the flow in order to deflect oil away from areas which are environmentally sensitive or to divert oil into calmer waters where conditions are more favourable for control and clean up. To be successful, a boom must completely divert an oil slick around it and not allow any oil to flow under. The angle at which a boom can be placed to the flow for successful diversion depends on flow conditions and oil properties. However, data for the use of booms as diverters are not available and guidelines do not exist.

The dynamics of the flow around and under an angled barrier is rather complex. In this study, a dimensional analysis of the problem is used to guide an experimental investigation.

The parameter under investigation is the maximum value of the angle at which a barrier can be placed to the flow and still completely divert an oil slick (Figure 2). This maximum angle, Θ_m, should depend on U_o, d_o, g, Δ, ρ , as well as the boom draught T, the water viscosity μ and the oil viscosity μ_o. Using dimensional analysis and assuming that density difference is important only in conjunction with gravity force, one can write

$$\Theta_m = \Phi \left[\frac{U_o}{(g\,\Delta T)^{1/2}}, \frac{T}{d_o}, \frac{U_o\,T\,\rho}{\mu}, \frac{\mu_o}{\mu} \right] \tag{9}$$

in which Φ indicates a function.

For fully turbulent flow conditions, the effect of viscosity can be neglected and one can write

$$\Theta_m = \Phi \left[\frac{U_o}{(g\,\Delta T)^{1/2}}, \frac{T}{d_o} \right] \tag{10}$$

Experiments were carried out to establish the functional relationship in equation (10).

3.0 EXPERIMENTS

Laboratory experiments were performed in a tilting flume with a 15 metre long and 0.6 metre wide test section. The bottom of the flume was roughened with graded sand and the sides were smooth glass. The barrier which was deployed normal to the flow spanned the whole width of the flume and could be raised or lowered vertically by means of a screwjack. The barrier used for deflection was pivoted at one end and the other end could be positioned by a rod running in two parallel horizontal circular grooves cut in a plywood guide. Velocity measurements were made with a miniature current meter. Measurements of oil slick profiles were made with a point gauge which was a conductivity type probe with a servo mechanism which allowed it to follow the oil-water interface.

The oils used were obtained from Jetco Chemicals in Corsicana, Texas. These were synthetic oils which could be blended to give different viscosities and densities. The oils were bright red in colour which made observations easy. The oil properties are given in Table 1.

3.1 Failure Criteria

After uniform flow conditions were established, the barrier was lowered to the desired barrier draught. A few litres of oil were then introduced into the surface of the flow and the observation was made whether the oil was retained upstream of the barrier. If no oil at all was retained by the barrier then the test was deemed a "failure". The boom draught was altered and the test repeated. It was discovered that the boom draught did have an effect on whether there was "failure" or not. Therefore, at any given flow condition, tests were performed over a range of values of boom draught.

3.2 Slick Profile and Interfacial Friction

In these tests, the barrier was lowered and a measured volume of oil was injected into the flow. The slick was allowed to reach an equilibrium in front of the barrier. The barrier was then cranked up very slowly and stopped when the first drop of oil escaped underneath. The barrier draught and slick profile were then recorded. The barrier was lowered again and more oil was added and the procedure repeated.

Tests were performed at different flow conditions, with different bottom roughnesses and different oils.

3.3 Diversion

After flow conditions were established, the barrier was positioned at some angle to the flow. Two and a half litres of oil were then released into the flow and observations were made to determine whether or not all the oil flowed to the end of the barrier and then downstream. If any oil at all passed under the barrier, the angle was reduced and the test was repeated until complete diversion was achieved. If all the oil was diverted in the first test, the angle Θ was increased until oil started to flow under the barrier. In this manner, the maximum angle for diversion, Θ_m, was established. Tests were conducted using two different oils.

4.0 RESULTS AND DISCUSSION

4.1 Failure Criteria

Over ninety tests were made to determine the failure criteria. The flow depths used varied between 20 centimetres and six centimetres and F varied from 0.57 to 0.12. The complete data can be found in another report (6).

Figure 3 is a plot of the boom draught to flow depth ratio, T/d_o, against densimetric Froude number F for all the tests. It can be seen from Figure 3 that for $F > 0.5$, there was indeed no successful containment at all. This verifies the failure condition given by Wilkinson. However, there were failures even when the Froude numbers were much less than 0.5. For a given value of F less than 0.5, there was a minimum value of T/d_o below which the barrier could not contain any oil. This minimum value of T/d_o decreased with decreasing F as shown by the dashed line in Figure 3. There is no distinction between the results for the two different oils which indicates that oil viscosity is not a factor in determining this type of failure.

The failure of the barrier at values of F less than 0.5 is interesting because, according to the theory, no failures are predicted and there should have been stable slicks with frontal thicknesses given by equation (1). Observations showed that as the oil impinged upon the barrier it seemed to be carried down by its own momentum and then flowed underneath the barrier. The failures appeared to be the result of the barrier halting the momentum of the oil. In an attempt to verify this, a number of the tests for $F < 0.5$ were repeated. The barrier was initially set deep enough for containment and a slick was allowed to collect. The barrier was then slowly cranked up. As the draught became less than the oil thickness, some oil escaped until the oil thickness was equal to the draught. It was found that the barrier could be raised in this manner to the point where failure occurred in the original test and a stable slick would still remain. However, when the barrier was raised to release all the oil and then reset to the same draught, any oil which was released upstream and flowed to the barrier would flow under as it reached the barrier. Thus, it appears that this mechanism of failure is the downward deflection of the oil as it reaches the barrier, which is a mechanism not covered by the steady state equilibrium analysis of previous writers.

A very simple model can be developed to check the results of these failures. Assuming that no momentum is destroyed upon reaching the barrier, an oil particle has verticle velocity v equal to U_o as it starts to move downwards. By neglecting the shear forces and assuming that only buoyancy retards the downward motion of the oil, one can write

$$-\frac{d}{dt}(\rho_o v) = (\rho - \rho_o) g \qquad (11)$$

in which t = time. The initial condition is $v = u_o$ at $t = 0$.

Solving equation (11), one finds that the downward distance travelled by the oil when its vertical velocity has decreased to zero is $U_o^2/(2 \frac{\Delta}{1 \Delta} g)$. Therefore, to prevent the oil from passing underneath the barrier, the barrier draught T has to be greater than $U_o^2/(2g\Delta/1-\Delta)$.

Even though the above-mentioned criterion has nothing to do with the flow depth d_o, one can divide d_o into both sides and obtain the condition

$$\frac{T}{d_o} > F^2 \left(\frac{1-\Delta}{2}\right) \qquad (12)$$

Equation (12) can be used to check the test results given in Figure 3. The data from Figure 3 for $F < 0.5$ are plotted on an expanded scale in Figure 4 together with the curve $T/d_o = F^2 (1-\Delta)/2$. According to equation (12) there should be containment above the line and failure below it. Very good agreement with this is shown in Figure 4, which is rather fortuitous considering the very simplistic model which was used. Nevertheless, this serves to illustrate the type of failure mechanism which was encountered.

Based on these results, there are two criteria for the containment of oil slicks by barriers in open-channel flows, namely

$$F < 0.5$$

and (13)

$$T > \frac{U_o^2}{2 \frac{\Delta}{1-\Delta} g}$$

The second criterion may be important when trying to contain heavy oils in fast flowing rivers. For example if U_o = 1 m/s and Δ=0.08, then T has to be larger than 0.58 metres. Any boom with draught less than 58 centimetres would be useless.

4.2 Interfacial Friction Factor

Slick profiles were measured in six tests. Three different types of oil were used. With the number one oil, four slicks of different lengths were measured. One profile each was measured for the other two oils. The densimetric Froude number was kept constant for all six runs. Table 2 lists the test data.

Using the oil thickness at the barrier as the starting point, equation (7) was integrated in the upstream direction to obtain the slick profile and the total length of the slick. The value of D in equation (7) was taken to be 1.0 since the total depth was found to be practically constant. The integration was carried out using various values of f_i and the one which gave the calculated slick length equal to the measured length was taken to be the correct value of the average interfacial friction coefficient for that slick. The values of f_i so derived are given in Table 2.

The value of f_i for the number one oil was found to be about 0.022 which is very close to those found by Cross and Hoult (2). The Reynolds number based on the upstream flow conditions was about 3.7 x 10^4 which was also of the same order as those in (2). Wilkinson (10) reported f_i values of about 0.006 for Reynolds numbers of about 10^4. These values are lower even then the f_i values given by Ippen and Harleman for laminar flow between two layers of different density (3). As pointed out by Jain (4), the results of Wilkinson might have been affected by the difficulty in measuring the interfacial slope.

The values of f_i derived from the measurements with the number three and number four oils are 0.040 and 0.048 respectively. These values are much larger than that for the number one oil. Since the densimetric Froude numbers were the same and the Reynolds numbers were only very slightly different, the most likely factor which could have caused the difference in f_i was the oil viscosity. The number three and number four oils had viscosities of 74 cp and 390 cp respectively while the number one oil had a viscosity of 8 cp. It appears from the results that the average interfacial friction coefficient increased with the oil viscosity. More comments will be made on this point later.

It has been pointed out by Wilkinson (10) and Bata (1) among others, that f_i is acutally not a constant but varies along the length of the wedge. A consequence of using a constant f_i for the whole slick is that the calculated slick profile will not be correct even though the slick length can be made equal to the measured one. This was true for all six runs although the deviations were not great. The slick volumes computed from the calculated profiles might have been about ten percent less than the actual volumes.

To investigate how the local value of f_i varies along the slick, an iterative procedure was used with equation (7). The measured slick profile was divided into a number of reaches and f_i was assumed to be constant for each reach. Starting at the downstream end, equation (7) was integrated using different values of f_i until the correct change in oil layer thickness between the ends of the reach was found. This gave the f_i value for the first reach. The integration then moved on to the next reach upstream. The local values of f_i for the whole slick were thus obtained.

The local f_i values are plotted in Figure 5 against the Reynolds number $U_o \ell \rho / \mu$ in which ℓ is the downstream distance measured from the start of the slick. For the sake of clarity, not all the data points are plotted. It can be seen that for all the slicks the f_i values decreased with the Reynolds number. There is a changing shear stress along the interface because of the developing of a boundary layer as water flows along the oil layer. Schlichting (7) has shown that for the case of a boundary layer flow along a smooth flat plate, the local friction coefficient decreases along the plate and varies with Reynolds number to the minus one-fifth power. Although this is not exactly analogous to the present case, it can be seen in Figure 5 that $f_i \sim R^{1/5}$ is not a bad approximation for the present data. Because of this, one can see that the use of an average f_i for the whole slick would not result in the the correct slick profile. However, for estimation of slick volume, an average f_i may be adequate.

The local f_i values, like the average values, showed an increase with increasing oil viscosity. Although there is no clear reason why the friction coefficient should be affected by the oil viscosity, the experimental evidence indicates that there is a definite effect. This may be a result of the way in which the interfacial shear stress was defined, i.e.

$$\tau_i = \frac{f_i}{4} \rho \frac{U}{2} \qquad (5)$$

Strictly speaking, τ_i ought to be related to the relative velocity between the water and the oil instead of just the water velocity U. However, the average velocity in the oil layer is zero even though there is a circulation in the oil. The circulation velocity was likely to be smaller for the more viscous oil. Therefore, the interfacial shear stress was probably larger when the oil was more viscous because of a larger relative velocity. The increase in shear stress had to be accounted for by an increase in f_i because, in the one-dimensional formulation, the average velocity in the slick had to be used and its value was always zero. There is no doubt that the interfacial stress was larger for the more viscous oils because, with the same flow conditions and same boom draught, the viscous slicks were all shorter than the less viscous slicks.

4.3 Diversion

The maximum angle for successful diversion was obtained in about sixty tests. T/d_o ratio varied between 0.1 and 0.5 and two different oils were used. The results are plotted as Sin Θ_m versus F_T in Figure 6, in which $F_T = U_o/(g\,\Delta T)^{1/2}$, the densimetric Froude number based on the boom draught.

The results indicate that Sin Θ_m decreases with F_T as expected. However, there does not appear to be any definite effect of the ratio T/d_o. There is some scatter in the data which may be caused by the fact that the boom angle could only be read to the nearest two degrees. Furthermore, the decision regarding when the maximum angle was reached was somewhat subjective. However, observations tended to show that it was the flow at the immediate vicinity of the barrier which determined if the oil could be diverted and it should not be too surprising that the depth of water had relatively little effect.

The results for the number three oil were about the same as for the number one oil. Therefore, oil viscosity also had little effect on Θ_m.

In observing the losses occurring underneath an angled barrier, it was seen that failure sometimes occurred due to the oil flowing under as a sheet and at other times due to droplets being torn off the slick and carried underneath. Therefore, the oil-water interfacial tension may be a factor in the success or failure of diversion. However, there were not enough data for a study of this factor to be made.

The line drawn in Figure 6 indicates the lower bound for Sin Θ_m. The empirical relationship for this lower bound is

$$\sin \Theta_m = 0.63 F_T^{-0.87} \qquad (14)$$

For a boom with a given draught in a given current equation (14) can be used to estimate the maximum angle at which the boom can be set to the current for complete diversion of an oil slick of a given density.

5.0 SUMMARY

Laboratory experiments have confirmed that oil containment by a boom is impossible when the densimetric Froude number of the flow is greater than about 0.5. In addition, a new condition for successful containment was discovered. This condition is the result of oil being deflected downward as it reaches the barrier. Based on the test data and a simple model, this condition can be stated as

$$T > \frac{U_o^{\,2}}{\left(\frac{2\,\Delta}{1-\Delta}g\right)}$$

This criterion may be significant for the containment of heavy oils in a fast current.

Measured slick profiles were used to calculate the average interfacial friction coefficient as well as the local values of the coefficient along the slick. It was found that the local values of f_i decreased with distance along the slick. However, for the practical purpose of estimating slick volume, an average f_i may be adequate.

The friction coefficient was found to increase with increasing oil viscosity. The interfacial shear stress was larger for the more viscous oils, probably because of a smaller circulation velocity in the oil and hence a larger relative velocity between the oil and the water. With the present definition for f_i, which is appropriate for a one-dimensional analysis, this increase in interfacial stress shows up as an increase in f_i.

Tests on diversion of oil by an angled barrier were used to establish an empirical relationship between the maximum angle for the barrier and a densimetric Froude number based on boom draught.

APPENDIX I - REFERENCES

1. Bata, G. L., "Recirculation of Cooling Water in Rivers and Canals", Journal of the Hydraulics Division, ASCE, Vol. 83, No. HY3, June 1957.

2. Cross, R. H. and Hoult, D. P., "Collection of Oil Slicks", Journal of the Waterways, Harbors, and Coastal Engineering Division, ASCE, Vol. 97, No. WW2, Proc. Paper 8122, May 1971, pp. 313-322.

3. Ippen, A. T. and Harleman, D.R.F., Steady-State Characteristics of Subsurface Flow, "Gravity Waves", National Bureau of Standards Circular 521, November 28, 1952, pp. 79-94.

4. Jain, S. C., Discussion of "Limitations to Length of Contained Oil Slicks", by D. L. Wilkinson, Journal of the Hydraulics Division, ASCE, Vol. 100, No. HY3, Proc. Paper, March 1974, pp. 492-494.

5. Maxwell, W.H.C., Discussion of "Limitations to Length of Contained Oil Slicks", by D. L. Wilkinson, Journal of the Hydraulics Division, ASCE, Vol. 100, No. HY3, Proc. Paper, March 1974, pp. 492-494.

6. Moir, J. and Lau, Y. L., "Experiments on Containment and Diversion of Oil by a Vertical Barrier", Unpublished Report, Hydraulics Research Division, Canada Centre for Inland Waters, November 1975.

7. Schlicting, H., "Boundary Layer Theory", 4th edition, McGraw-Hill, 1962.

8. Vanderkooy, N., Robertson, A. and Beckett, C.J., "Evaluation of Oil Spill Barriers and Deployment Techniques for the St. Clair-Detroit River System", Report EPS-4-EC-76-4, Environmental Protection Service, Environment Canada, June 1976.

9. Wilkinson, D. L., "Dynamics of Contained Oil Slicks", Journal of the Hydraulics Division, ASCE, Vol. 98, No. HY6, Proc. Paper 8950, June 1972, pp. 1013-1030.

10. Wilkinson, D. L., "Limitations to Length of Contained Oil Slicks", Journal of the Hydraulics Division, ASCE, Vol. 99, No. HY5, Proc. Paper 9711, May 1973, pp. 701-712.

Table I - Oil Properties

Oil Type (1)	Δ (2)	μ_o/μ (3)
#1	0.163	7.14
#2	0.129	78.50
#3	0.115	66.04
#4	0.085	348.09

Table 2 - Data for Experiments on Interfacial Friction Coefficient

Test Number	Oil Type	Mean Velocity, U_o, in metres per second	Flow depth, d_o, in metres	Δ	Bed Friction Coefficient, f_b	Densimetric Froude Number, F	μ_o / μ	Interfacial Friction Coefficient, f_i
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	#1	0.118	0.122	0.163	0.029	0.267	7.14	0.021
2	#1	0.118	0.122	0.163	0.029	0.267		0.023
3	#1	0.119	0.122	0.163	0.029	0.267		0.022
4	#1	0.119	0.122	0.163	0.029	0.267		0.021
5	#3	0.099	0.120	0.115	0.025	0.270	66.04	0.040
6	#4	0.086	0.119	0.085	0.026	0.271	348.09	0.048

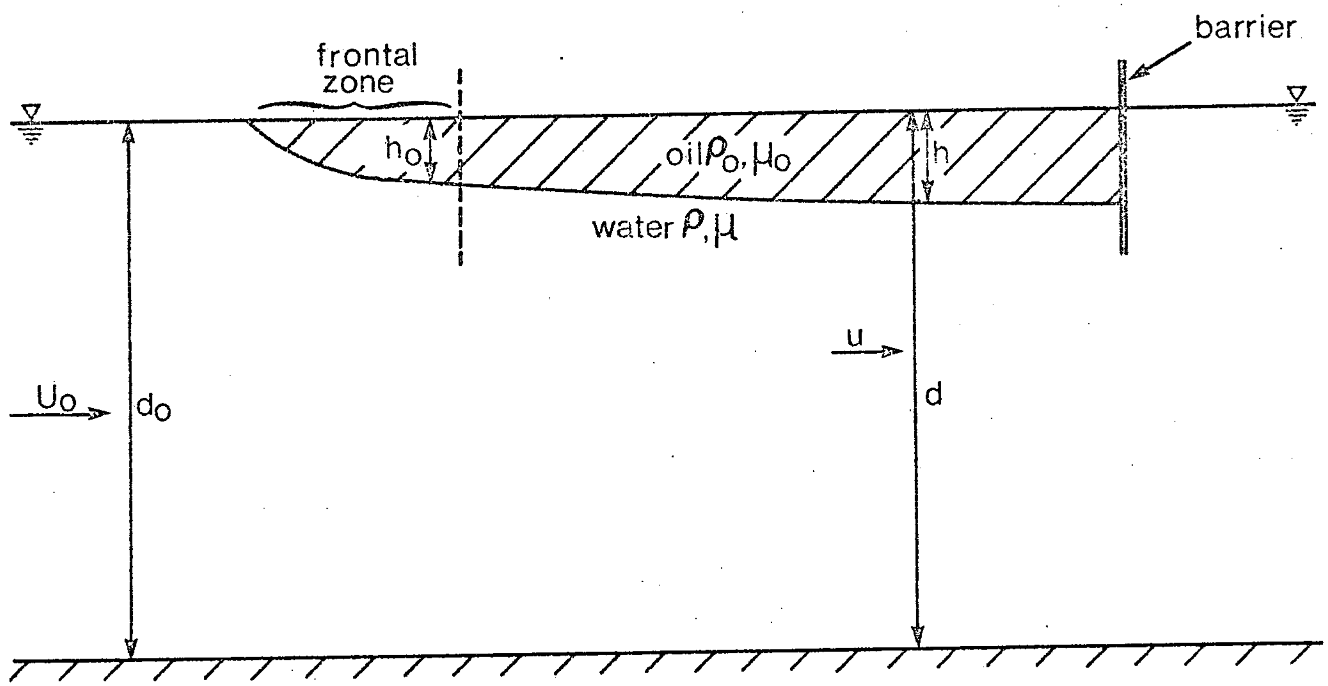

Figure 1 Definition Sketch

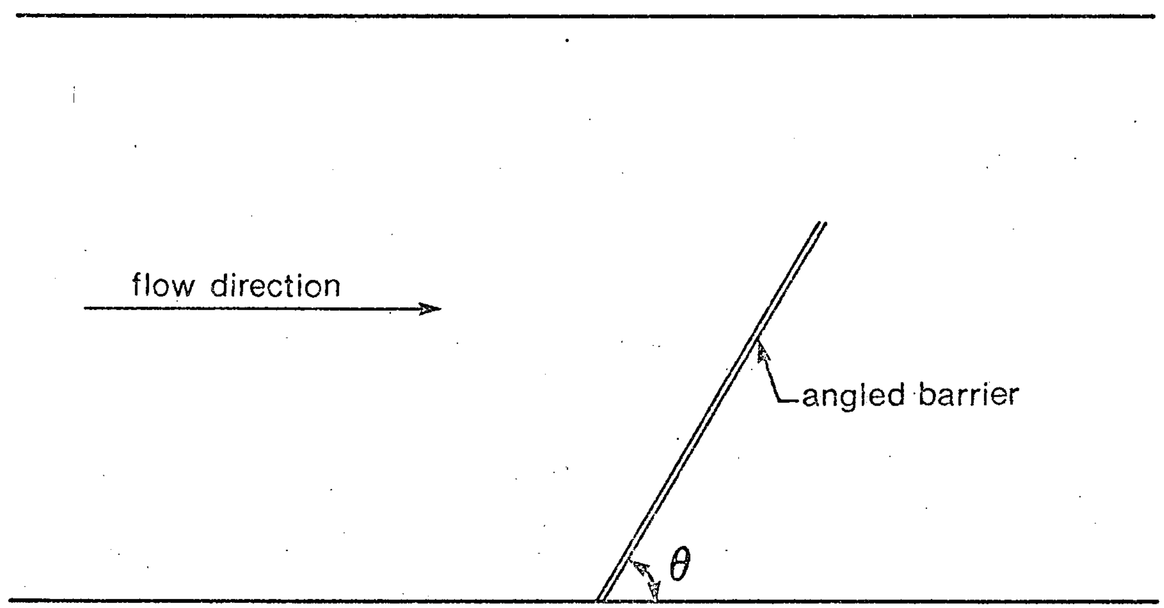

Figure 2 Plan View of Barrier for Oil Diversion

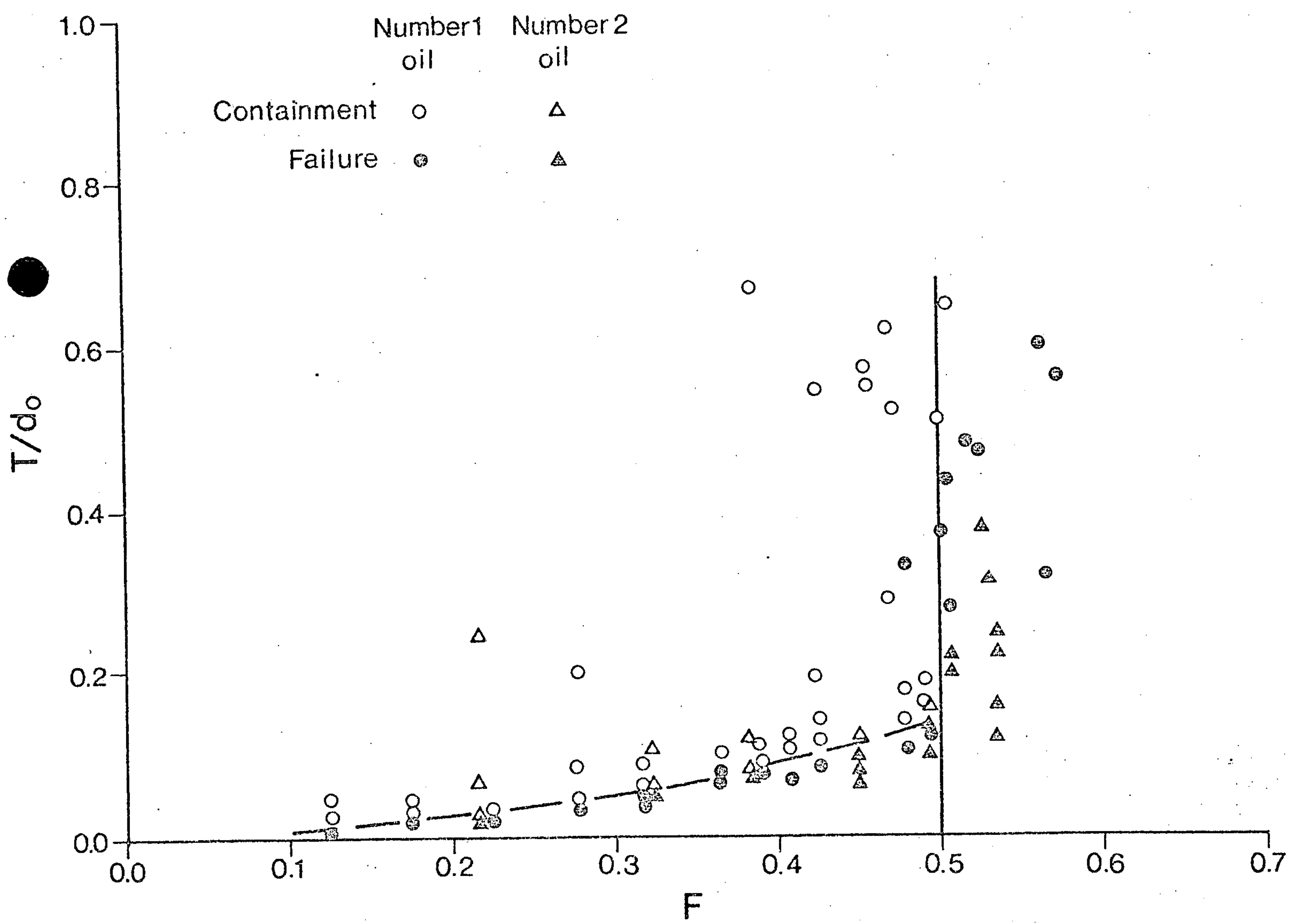

Figure 3 Effect of F and T/d_o on Containment

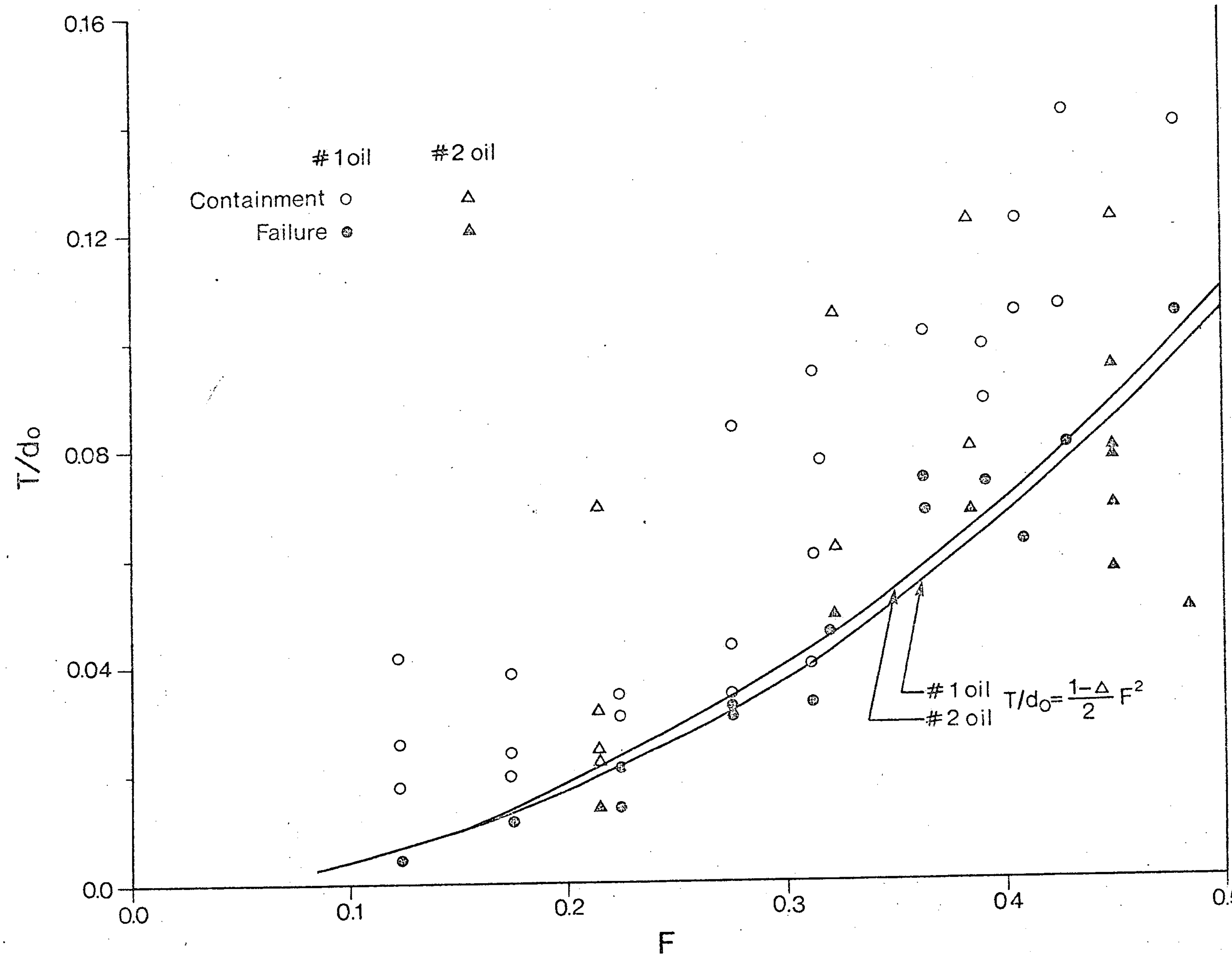

Figure 4 Failure Criteria for Froude Number Less than 0.5

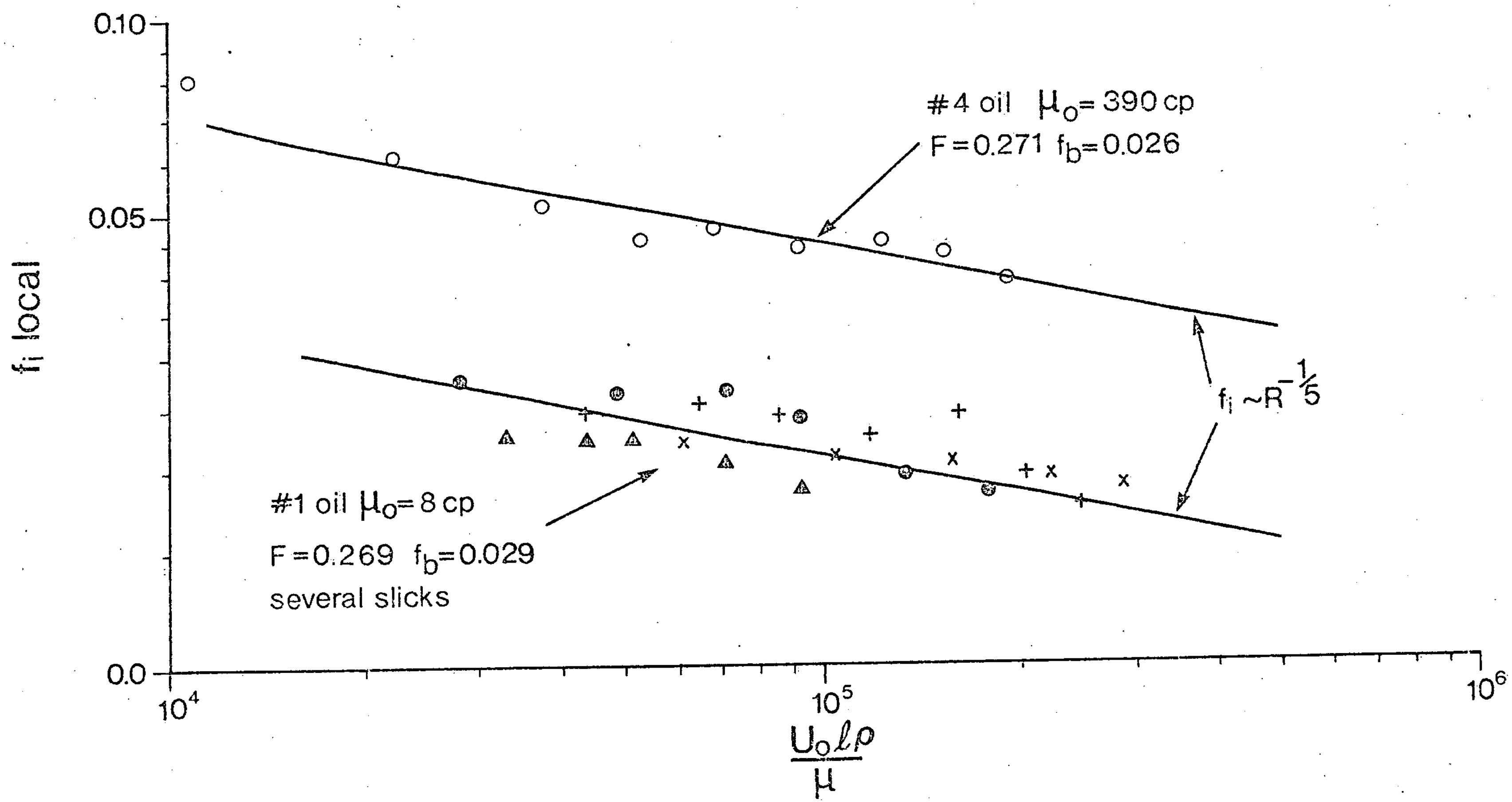

Figure 5 The Variation of the Local Values of the Interfacial Friction Coefficient with Reynolds Number

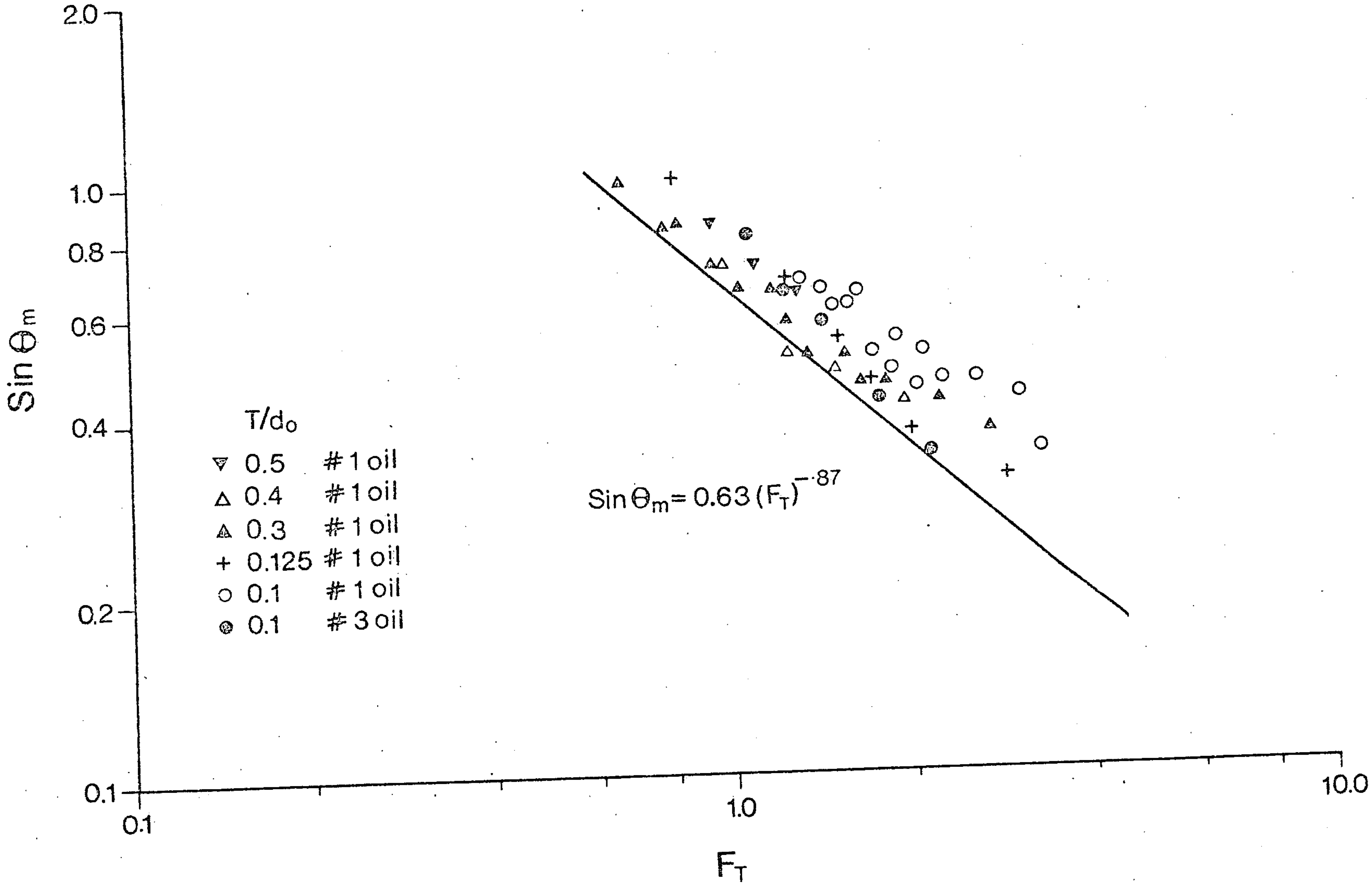

Figure 6 Maximum Angles for Successful Diversion as a Function of F_T

APPENDIX II - NOTATION

The following symbols are used in this paper:

D = the ratio between total depth d and depth upstream of slick d_o;
d = total depth;
d_o = depth upstream of slick;
F = densimetric Froude number;
F_T = densimetric Froude number based on boom draught T;
f_b = bottom friction coefficient;
f_i = interfacial friction coefficient;
g = gravitational acceleration;
H = ratio between slick thickness h and depth upstream d_o;
H_m = maximum slick thickness;
h = slick thickness;
h_o = slick frontal thickness;
ℓ = downstream distance measured from upstream edge of slick;
T = boom draught;
t = time
U_o = mean velocity upstream of slick;
u = mean velocity under slick;
v = vertical velocity component;
X = ratio between downstream co-ordinate and depth upstream d_o;
x = co-ordinate in downstream direction;
Δ = ratio between oil-water density difference and water density;
ρ = water density;
ρ_o = oil density;
μ = kinematic viscosity of water;
μ_o = kinematic viscosity of oil;
Φ = a function
ϕ = ratio between frontal thickness of slick h_o and depth upstream d_o;
τ_b = bottom shear stress;
τ_i = interfacial shear stress;
θ = angle between boom and downstream direction;
θ_m = maximum value of angle θ.