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EXPERIMENTS ON CONTAINMENT AND DIVERSION OF OIL BY A VERTICAL BARRIER

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SUMMARY

Using dimensional analysis, the variables which govern the containment and diversion of oil slicks by barriers in riverflow are identified. A laboratory test programme was carried out to determine the criteria for containment, guidelines for volume of oil containable and diversion of oil by barriers angled to the flow. The relative barrier draft and the flow friction factor, parameters previously ignored, have been shown to be important factors. Suggestions for further laboratory work and field tests are made.

LIST OF SYMBOLS

Symbol	Dimension	Meaning
b	L	channel width
B		constant in logarithmic velocity distribution
d	L	channel depth
e	L	mean sand grain size of bottom roughness
f_b		flow friction factor
f_i		interfacial friction factor
$F_\Delta = u/\sqrt{g\Delta d}$		densimetric Froude number
$F_{\Delta t} = u/\sqrt{g\Delta t}$		densimetric Froude number
$F_s = u/\sqrt{g\Delta\delta}$		densimetric Froude number
g	L/T^2	gravitational constant
h	L	thickness of oil layer
k		numerical constant describing droplet formation
k_D		numerical constant describing angle barrier failure by droplet formation
k_H		numerical constant describing angle barrier failure by headwave "under-topping"
k_s	L	equivalent sand grain roughness
$R_e = ud\rho/\mu$		Reynolds number
S		free surface slope
t	L	barrier draft
T	T	time
u	L/T	average flow velocity
W_e		Weber number used by Hale et al

Symbol	Dimension	Meaning
x	L	distance from leading edge of slick
X		a dimensional property of slick containment or diversion
χ		a dimensionless property

GREEK SYMBOLS

δ	L	headwave thickness
$\Delta = (\rho - \rho_o)/\rho$		dimensionless measure of oil density
θ	degrees	angle of barrier to the flow, equal 0^o when parallel to flow
μ	M/TL	dynamic viscosity of water
μ_o	M/TL	dynamic viscosity of oil
π		3.14159...
ρ	M/L^3	density of water
ρ_o	M/L^3	density of oil
σ	M/T^2	surface tension and in this report for the oil/water interface
$\phi = \delta/d$		relative headwave thickness
Φ		denotes a mathematical relationship
Φ_a		for angled barriers
Φ_v		for contained volume

1. Introduction

Oil on water, if not hindered, spreads to a relatively thin slick that is awkward and inefficient to remove from the water surface. If pumps are used, large volumes of water are unnecessarily handled leading to greater costs in pumping and difficulties in separation of oil from water afterwards. Oil can be much more efficiently removed from the water surface, and not just by pumps, if the slick is caused to thicken, for example, against a floating barrier by the flow of a river.

The containment of diversion of oil on a river where the current and relatively shallow depth are of great importance, is very much different from on a lake or ocean where wind and waves may predominate. On an open body of water, barriers are limited in use by the structural loads imposed by waves but on a river, barriers are limited in use by the effects on shape and stability of the contained slick, imposed by the riverflow.

However it has been found in practice that, if the river current is too fast, containment is not possible and the oil must be diverted to the riverbank where the flow is usually much slower.

Review of Previous Work

Lau and Kirchheffer (1)* have reviewed theories** of slick containment in a river situation and concluded that "the analysis of Wilkinson is probably the most reliable one" (2). The authors have reviewed, in addition, two United States Coast Guard reports (3,4) and still agree with that statement.

The analysis of Wilkinson (5,6) suggests two limitations on the stability of slicks. One based on the analysis of the headwave region of the slick suggests that the headwave thickness and the other flow properties are related by the following equation:

$$F_\Delta^{\,2} = \phi\,(2-\phi)\left[\left(\frac{2\phi}{1-\phi} + \frac{1}{1-\Delta}\right)\right]^{-1} \qquad (1.1)$$

where U = upstream velocity

g = gravitational acceleration

d = upstream flow depth

---

* numbers in brackets refer to references

** See Appendix A

Δ = 1-(S G of oil)

F_Δ = $\frac{u}{\sqrt{gd\Delta}}$, densimetric Froude number

ϕ = δ/d

δ = headwave thickness

For values of F_Δ larger than about 0.5 equation (1.1) has no solution and this value of F_Δ was taken to be the critical value above which no slicks can form. The equivalent value of ϕ is about 0.3. The second limitation gives a critical thickness of the viscous region of the slick which is closely approximated by:

$$\frac{h}{d} = 1 - F_\Delta^{2/3} \qquad 1.2$$

where h = slick thickness in viscous region.

Even at high F_Δ, near the failure given by equation (1.1), h/d approaches a minimum of about 0.37. Thus, for a failure to be governed by the mechanisms detailed by Wilkinson the barrier draft would have to be at least 0.3 to 0.37 of the flow depth, and this seems impractical for all but the shallowest streams.

Commercial booms usually range in draft from six inches to 36 inches, and, on a river of average depth of 20 to 25 feet, such as the St. Clair, therefore have relative draft to depth ration of 0.02 to 0.15. At such small relative draft ratios, the slick would flow under the barrier, before actual instability of the slick occurred.

Other authors such as Cross and Hoult (7,8) Lindenuth, Miller and Hsu (3) or Hale, Norton and Rodenburger (4) have not included flow depth as a variable, and as such the relative draft ratio certainly does not appear. These authors' analyses assume infinite depth, although a practical definition of what infinite depth is, is not presented.

Wilkinson has included the flow friction factor, f_b, as a variable in his theoretical work but did not vary f_b in his experimental program. Analyses that do not include depth as a parameter <u>necessarily</u> cannot include f_b as a parameter. The influence of f_b has not been verified experimentally.

The report by Hale, Norton and Rodenberger (3) ascribes the instability, in a current, of the headwave of a slick entirely to entrainment losses by droplet formation. Droplets are produced in such quantities, that the oil leaks under the barrier, in a very short time. The oil is not emulsified or suspended in the water, but reforms a thin slick downstream of the barrier. Hale et al suggests that this failure can be described by a constant Weber number, W_e, given by:

$$We = \frac{\rho u^2}{\sigma g(\rho - \rho_o)}$$

Their experiments were performed at a constant depth of 3.5 feet, and in addition to the results of Hale et al, Table 1.1 lists the densimetric Froude number, F_Δ. It would seem that the results equally well support the argument that the droplet entrainment failure can be described by a constant densimetric Froude number, F_Δ.

TABLE 1.1

Oil Type	Critical Velocity (ft/sec)	Specific Gravity	Interfacial Tension (dynes/cm)	Viscosity (cP)	We	F_Δ
No. 2 Diesel	1.25	0.846	17.0	3.9	28.6	.300
No. 2 Diesel	1.30	0.840	23.0	3.9	26.1	.306
SAE 30	1.12	0.883	13.0	222	30.1	.308
SAE 30	1.09	0.890	12.0	183	30.6	.310
SAE 40	1.00	0.895	11.0	565	27.6	.291
SAE 140	1.00	0.920	16.3	1867	26.0	.333

The barrier drafts used are not stated, however, it is mentioned that the flow depth was always at least 10 times the slick thickness.

Lindenmuth, Miller and Hsu (4) attempted to model containment in theory by considering a critical densimetric Froude number, $u/\sqrt{g\Delta\delta}$, equal to 1.0 and a critical Weber number, and in practice by towing a barrier along a 24 by 24 inch still water tank. A constant relative draft ratio of 0.25 in 20 inches of water was used. Although the effective width to depth ratio for the water is infinite, the motion of the contained slick along the tank would produce large secondary currents in the slick and therefore the measurements of slick shape are suspect.

Lindenmuth et al suggest that failure is by two mechanisms, droplet formation and "drainage", which occurs when the barrier draft, t, is insufficient for the volume of oil. They suggest that the maximum barrier Froude number $u/\sqrt{g\Delta t}$ for which oil can be theoretically contained is 1.29, and that by experiment, the limiting condition is when $u/\sqrt{g\Delta t} = 1.0$. No experiments were conducted to determine maximum volumes containable.

An attempt has been made to scale the entrainment losses exactly, according to the Weber number given by:

$$W_L = \frac{u}{(\sigma\Delta\ g)^{1/4}}$$

This Weber number was varied experimentally by changing the interfacial tension, σ, with oil additives, so that the size of oil droplets would also be scaled. But entrainment losses are as much controlled by how the droplet is forced back to the slick as how the droplet is ejected from the headwave, and such important effects as turbulent suspension of the oil particles have been ignored. This gives rise to doubts that entrainment can be modelled on anything but the prototype scale.

Experiments with barriers angled in the horizontal plane showed only that retention was similar to the case of the barrier perpendicular to the flow.

There is an evident need for a careful and complete experimental investigation of the behavior of an oil slick contained behind, or diverted by a barrier subject to the flow conditions typical of a river.

Aim of the Report

Previous work on the behavior of oil on a river flow has been reviewed and generally found lacking in three areas:

1) Some important variables have not been included in either the theoretical or experimental work or both;
2) Most experiments appear to have been designed without thought to scaling the results to prototype;
3) No criteria for placing of barriers at angles to flow to divert oil to the side of the flow, exist.

It is the aim of this report, using experiments whose results can be readily scaled to prototype, to demonstrate the importance of these missing variables, and to establish guidelines for diversion of oil on a river flow.

2. DIMENSIONAL ANALYSIS

The theory of dimensions provides the method most likely to achieve the aims of this report, and therefore the relations describing containment and diversion are derived as follows:

Any property, X, of oil containment behind a barrier perpendicular to the flow may be described in the most general form as:

$$X = \Phi\ (u,\ b,\ d,\ e,\ t,\ \rho,\ \rho_o,\ \mu,\ \mu_o,\ \sigma,\ T,\ g) \qquad (2.1)$$

where:

u	= average velocity of water in channel	L/T
b	= channel width	L
d	= channel depth	L
e	= equivalent sand grain roughness of the channel	L
t	= barrier draft	L
ρ	= density of water	M/L^3
ρ_o	= density of oil	M/L^3
μ	= dynamic viscosity of water	M/LT
μ_o	= dynamic viscosity of oil	M/LT
σ	= oil-water interfacial tension	M/T^2
T	= time	T
g	= acceleration due to gravity	L/T^2

This equation may be expressed in dimensionless form as:

$$X^1 = \Phi_x\ \left(\frac{b}{d}, \frac{e}{d}, \frac{t}{d}, \frac{\rho_o}{\rho}, \frac{ud\rho}{\mu}, \frac{ud\rho}{\mu_o}, \frac{u^2 d\rho}{\sigma}, \frac{uT}{d}, \frac{u}{\sqrt{gd}}\right) \qquad (2.2)$$

If the flow is sufficiently wide (9) then the centre portion becomes two-dimensional and the variable b/d can be eliminated from equation (2.2). Further, if only properties, X^1, which are steady-state, or independent of time, are considered then the parameter $\frac{uT}{d}$ can be eliminated from equation (2.2). This is not unreasonable, since in the prototype it may be necessary to retain the oil behind a barrier for several days to allow for cleanup, and the volume contained is one such property, X^1.

The ratio ρ_o/ρ may be replaced by the density difference, Δ, which is $(\rho-\rho_o)/\rho$. Also in this problem the effect of density is important only when considered in conjunction with the gravity force. Therefore Δ can be combined with $\frac{u}{\sqrt{gd}}$ to form the densimetric Froude number $\frac{u}{\sqrt{g\Delta d}}$. Further, most prototype river flows are fully developed rough turbulent (10) and as such the relative roughness, e/d, is also equivalent, in equation (2.2) to f_b. Equation (2.2) now can be written as:

$$X^1 = f^1(t/d,\ f_b,\ u/\sqrt{g\Delta d},\ \frac{ud\rho}{\mu},\ \frac{ud\rho}{\mu_o},\ \frac{u^2d\rho}{\sigma}) \qquad (2.3)$$

The parameter $\frac{ud\rho}{\mu}$ is the Reynolds number, R_e, of the flow, and large values of R_e, variables, such as f_b, become independent of R_e, and as such R_e is no longer a controlling parameter. This prototype situation would happen in the laboratory if equipment is large enough so that R_e is greater than 10000.

The parameter $\frac{ud\rho}{\mu_o}$ can be divided by R_e giving the ratio μ_o/μ. The Weber number of the flow has been shown to be important in describing failure of entrainment of oil droplets torn off from the slick. Hale et al used the Weber number

$$W_e = \frac{\rho u^2}{\sqrt{\sigma g(\rho-\rho_o)}}$$

and found this number to be approximately constant in their experiments. It can be seen that this Weber number can be rearranged and written as

$$W_\epsilon = F_\Delta\sqrt{\frac{u^2d\rho}{\sigma}}$$

Lau and Kirchhefer (1) quoted the work of Christianson and Hixon and that of Hinze which, when taken together suggested that for droplet separation to occur,

$$F_\Delta \quad \frac{u^2 d\rho}{\sigma} \geq \frac{22}{\pi} \tag{2.4}$$

It is evident that when failure by droplet separation is important, the surface tension parameter plays an important role. However for other types of failure, it is felt that surface tension can be left out of consideration and equation (2.3) can be simplified to the following:

$$X^1 = \Phi_x \left(t/d,\ F_\Delta,\ f_b,\ \mu_o/\mu \right) \tag{2.5}$$

Volume of oil that can be contained behind a perpendicular barrier, is one such property X and the dimesionless volume parameter derived using the same procedure to get equation (2.2), is V/d^3, where V is the maximum volume of oil. For the two-dimensional case, the parameter is V/bd^2, which is the volume parameter used by Wilkinson. This parameter is appropriate for a study of the maximum slick for a flow, independent of the geometry of the barrier. As stated earlier in this report, such thick slicks are not likely to be achieved in practice; therefore the barrier draft is likely to govern the maximum slick size. A suitable volume parameter is V/bt^2: the equation describing the maximum volume of oil contained behind a barrier is:

$$\frac{V}{bt^2} = \Phi_v \left(\frac{t}{d},\ F_\Delta,\ f_b,\ \frac{\mu_o}{\mu} \right) \tag{2.6}$$

Failure, which can be regarded as zero contained volume, is the special case:

$$0 = \frac{V}{bt^2} = \Phi \left(t/d,\ F_\Delta,\ f_b,\ \mu_o/\mu \right) \tag{2.7}$$

Very often, barriers are placed at an angle to the flow in order to deflect the oil slick to a particular location. In this case, one is interested in the maximum angle θ at which the barrier can be placed such that all the oil is deflected by the barrier and none passes underneath the barrier. If $\sin\theta$ is used as the independent variable, where θ is the angle between the direction of flow and the normal to the barrier, one can write

$$\sin\theta = \Phi_a \; (t/d,\; F_\Delta,\; f_b,\; \mu_o/\mu) \qquad (2.8)$$

The above analysis shows that the significant independent variables for containment and diversion of oil slicks by barriers in a riverflow are:

1) the densimetric Froude number, F_Δ:

$$F_\Delta = \frac{u}{\sqrt{g\Delta d}}$$

2) the barrier relative draft ratio
3) the flow friction factor, f_b

where $$f_b = 8\,\frac{u_*^2}{u^2}$$

4) the viscosity ratio, μ_o/μ,

The failure mode caused by droplet separation, expressed by:

$$F_\Delta \cdot \sqrt{\frac{u^2 d\rho}{\sigma}} = \text{constant}$$

has been examined by other workers. Careful selection of the absolute size of the experimental set-up would assure that this mode would not mask other failure modes.

3. FACILITIES AND PROCEDURE

Three distinctly different test programs were run; one to determine failure criteria, one to determine maximum containable volume, and one to determine the capability of barriers angled to the flow for deflecting oil. All three series of tests were performed in the 1 metre tilting flume of the Hydraulics Research Division at the Canada Centre for Inland Waters in Burlington.

The tilting flume was used with a test length of 15 metres, a reduced width of 0.60 metre over the test section and a variable depth of 0.06 metre to 0.25 metre. The bottom of the flume was artificially roughened with various sizes of graded sand: the sides were smooth.

The same barrier was used in the failure and volume tests. The 10 cm by 59.5 cm blade was 0.50 inch plexiglas; the top and bottom faces were milled parallel. A machinist's bubble level and the blunt end of a gauge rested on the top surface of the blade. Each end of the blade could be raised vertically and independently, by means of a screwjack attached to the top of the flume. Guides, glued to the sides of the flume, above the waterline prevented horizontal motion of the blade. Rubber end seals prevented leakage.

For the angled-barrier tests, a 10 cm by 59.5 cm blade of 0.50 inch plexiglas with the lower edge sharpened, was pivotted at one end. The outer end of the blade was positioned by a rod running in two parallel horizontal circular grooves cut in a plywood guide. The clearance of the bottom edge of the barrier from the bottom was set for each test: the appropriate draft to depth ratio was set by controlling the depth of the flow.

Oil was injected on the surface of the flow with a grooved tray, sloped, which just touched the water surface. This allowed the oil to be placed on the flow in an even layer over the whole width of the flow without mixing either air or water into the oil. Oil was collected into settling tanks at the downstream end of the flume and recycled.

Experimental Procedure

For all tests the desired flowrate was established, and the downstream tailgate and bottom slope were adjusted to obtain uniform flow at the required depth.

For failure testing, the barrier was lowered to a desired barrier draft to flow depth ratio into the flow. A quantity of oil was injected onto the flow. After a period of waiting, the observation was made whether oil remained trapped upstream of the barrier. If no oil at all is retained by the barrier then the condition is deemed a "failure". The test was repeated at many t/d ratios until several observations of "failure" and "success" had been made at that flow conditions. The flow conditions were then changed and the cycle repeated. This procedure allowed the determination of a quite distinct range of t/d values where failure occurred.

After uniform flow was established for angled-barrier testing, the barrier was positioned at some angle. Two and one half litres of oil were injected onto the flow, and the observation was recorded whether any oil passed under the barrier. With bright red oil used under intense photographic flood-lights, very small droplets of oil could be visually detected. Further, if oil passed under the barrier, a sheen was visible on the surface of the flow, just downstream of the barrier. If any oil at all passed under the barrier, the test was repeated with a lesser angle to the flow. This cycle was repeated until the determination was made that at that flow condition, all the oil was diverted by the barrier. The testing was then repeated for a range of flow conditions, two values of barrier draft to flow depth, and two different oils. A parabolic (in plan) barrier was also tested.

Since the angle was measured to the nearest two degrees, this procedure produced a range in the value of the angle. At the higher value, a little oil escaped under the barrier and at the next lower value (about 2 to 5 degrees less), all the oil was diverted. For the purposes of this report the "maximum angle of diversion" is defined as the lower bound of the range.

Determinations of maximum containable volume behind a barrier perpendicular to the flow and estimates of interfacial friction factors were made from the same series of tests. After uniform flow had been established, the barrier was lowered about one-third of the depth into the flow. A small measured volume of oil, usually 500 or 1000 cubic centimeters, was injected onto the flow. The slick was allowed to reach equilibrium. The barrier was cranked up very slowly until the first drop of oil escaped. The clearance of the bottom of the barrier from the channel bottom, and the profile of the slick were recorded. The barrier was lowered. The cycle was repeated until five readings had been recorded. Another known quantity of oil was added and the sequence repeated until the draft to depth ratio exceeded 0.20. Flow rate and depth, bottom roughness, and oil density and viscosity were varied in the volume test series.

4. RESULTS

Two synthetic oils, obtained from Jetco Chemicals*, proportioned and mixed to give oils of varying densities and viscosities, were used in the tests as tabulated in Table 4.1 and Table 4.2

Table 4.1. Oil Properties of Failure and Angled-Barrier Series

Series	Test #	to #	Density gm/cc	Viscosity cP
Failure	1	65	0.837	8
Failure	66	97	0.871	88
Angled	1	61	0.837	8
Angled	66	70	0.883	76
Angled	71	76	0.837	8

Table 4.2. Oil Properties and Bottom Roughnesses of Volume Series

Test #	Oil Properties		Graded Sand Size
	Density gm/cc	Viscosity cP	mm
17	.837	8	1
28	.837	8	1
34	.837	8	10
43	.885	74	10
50	.837	8	2
57	.837	8	2
65	.837	8	2
73	.837	8	2
83	.837	8	2
89	.837	8	smooth
97	.903	253	smooth
103	.885	74	smooth
112	.837	8	smooth
118	.915	390	smooth

* Jetco Chemicals Inc., P. O. Box 1278, Corsicana, Texas, U.S.A.

The channel bottom was artificially roughened with 1 mm graded sand for the failure and angled-barrier series. The artificial roughness used in the volume series is also tabulated in Table 4.2.

The tabulated test results are given in Appendix E. Table E.1 summarizes the failure series, Table E.2 the volume series and Table E.3, the angled-barrier series.

5. DISCUSSION

Failure

The relationship describing failure is given by equation (2.7) as

$$0 = \frac{V}{bt^2} = \Phi_v \ (t/d,\ F_\Delta,\ f_b,\ \mu_o/\mu)$$

Figure 5.1 shows a plot of t/d versus F_Δ for $\Delta = 0.163$. The cases of containment and no containment are both shown. From these points a line can be drawn separating the regions of containment and no containment. This shows that the failure curve has two distinct limits; an upper limit to F_Δ of about 0.5 and a smooth curve when t/d is less than about 0.16.

As in equation (1.1) Wilkinson showed that a stable frontal region or headwave cannot exist when F_Δ is larger than about 0.5. In his theory this limit varies with $(1/1 - \Delta)$, but the data of these tests is not sufficient to show this small variance. For all practical purposes, these tests show that the upper limit of F_Δ for any containment is 0.5, and that this limit is independent of the barrier relative draft.

Two sets of points are shown in Figure 5.1, one for width to depth ratio b/d equal to 4 and one for b/d equal to 10. Since the bottom roughness remained the same this change in depth represents a change in relative roughness and thus f_b. From Figure 5.1 it can be seen that bottom sets appear to give the same failure curve. Therefore f_b appears to have little effect on the failure criteria.

Figure 5.2 shows the results of failure tests using an oil of different viscosity and density. The resulting failure curve is indistinguishable from the plot of Figure 5.1. Therefore it can be concluded that μ_o/μ also has little effect on the failure criteria and that for no containment the relationship is given by

$$0 = \frac{V}{bt^2} = \Phi_v \ (F_\Delta,\ t/d) \tag{5.1}$$

Therefore failure is completely governed by the two parameters, the relative draft ratio and the densimetric Froude number.

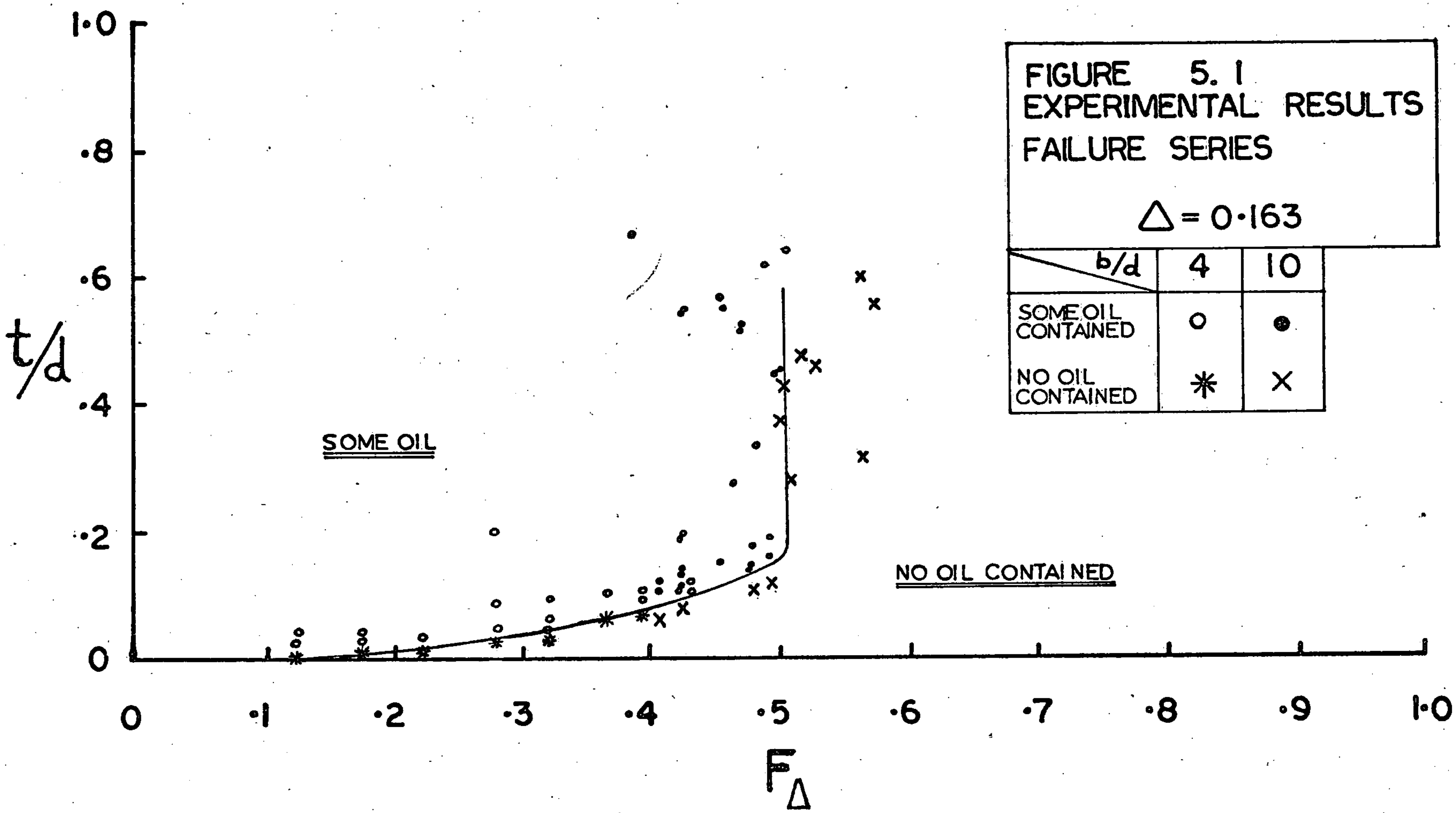


FIGURE 5.1
EXPERIMENTAL RESULTS
FAILURE SERIES

$\Delta = 0{\cdot}163$

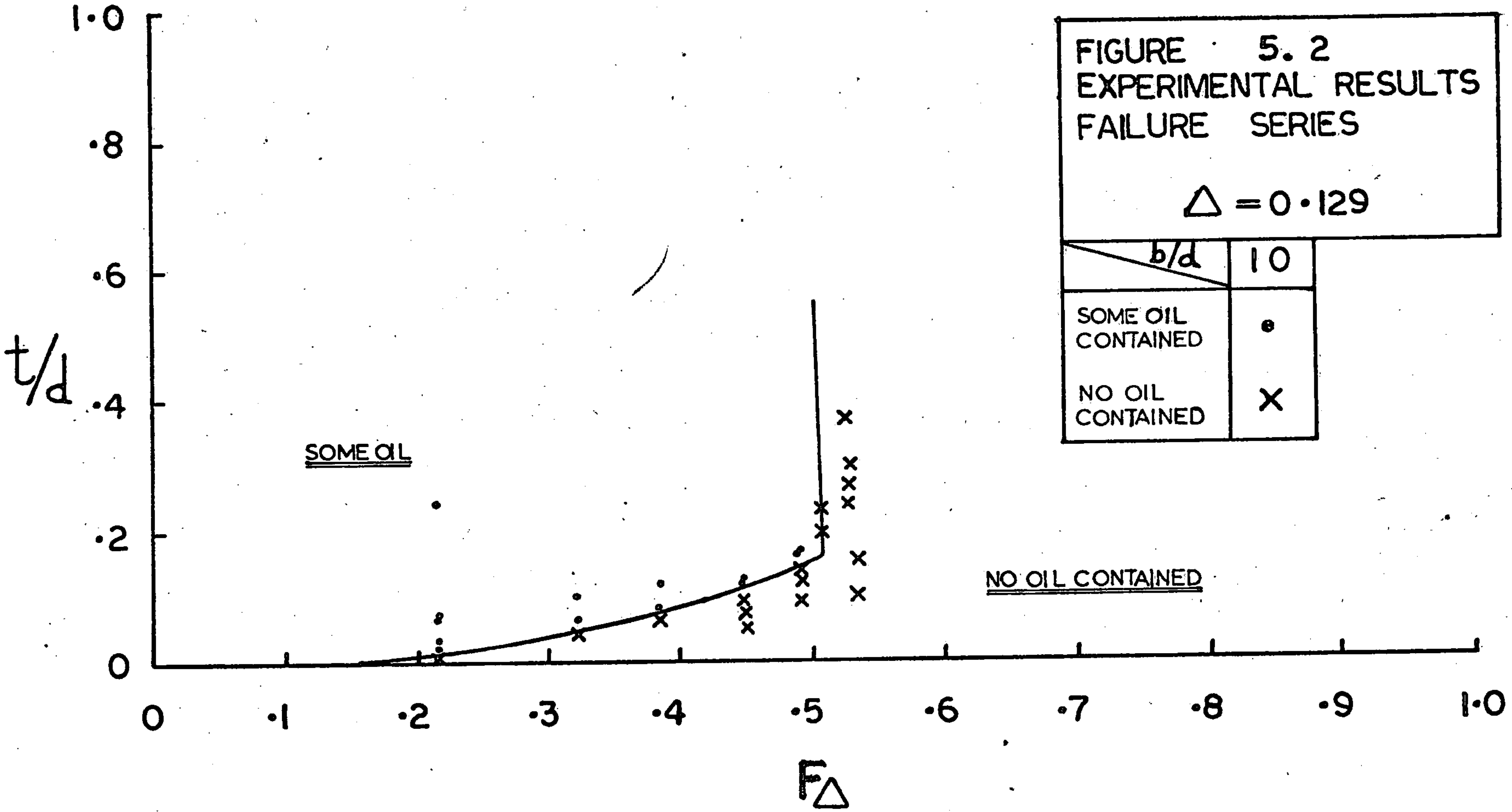


FIGURE 5. 2
EXPERIMENTAL RESULTS
FAILURE SERIES
△ = 0·129
b/d
10
SOME OIL CONTAINED
NO OIL CONTAINED
SOME OIL
NO OIL CONTAINED
t/d
1·0
·8
·6
·4
·2
0
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
F△

For F_Δ less than 0.5 the failure criteria varies with the boom draft ratio t/d. As shown in Figure 5.3, the failure points appear to follow the relationship

$$F_\Delta = \sqrt{2(1-\Delta)\ t/d} \tag{5.2}$$

However there is as yet no theoretical justification for this relationship.

Defining a densimetric Froude number based on the boom draft t as $F_{\Delta t} = u/\sqrt{g\Delta t}$, the empirical relationship (5.2) can be written as

$$F_{\Delta t} = \sqrt{2(1-\Delta)} \tag{5.3}$$

Equation (5.3) gives an upper limit of $F_{\Delta t}$ for oil containment, regardless of boom draft ratio or F_Δ. Figure 5.4 shows a plot of the experimental points in a t/d versus $F_{\Delta t}$ plot.

In these experimental tests for failure criteria, it was found that at the minimum t/d, for a particular F_Δ, for any containment, that the oil did not form a slick limited in thickness by the barrier draft. The slick thickness, δ was only a very small fraction of the barrier draft, t.

Volume

The maximum containable volume is described by equation (2.6):

$$\frac{V}{bt^2} = \Phi_v\ (F_\Delta,\ t/d,\ f_b, \mu_o/\mu) \tag{2.6}$$

Figure (5.5) shows test results with f_b and μ_o/μ kept constant and illustrates the expected large reduction in volume with an increas in F_Δ. However, Figure (5.6) shows that f_b as measured by the relative roughness e/d, also has a comparably significant effect.

Figure (5.7) which shows results for oils with about a 50 fold difference in viscosity demonstrates that the ratio μ_o/μ has only a small influence. With the least viscous oil, μ_o = 8 cPs, significant interfacial waves developed and at small values of t/d, a large allowance of barrier draft against "undertopping" was needed. Hence the line for μ_o = 8 cP shows that V/bt^2 is less than for more viscous oils at small t/d ratios.

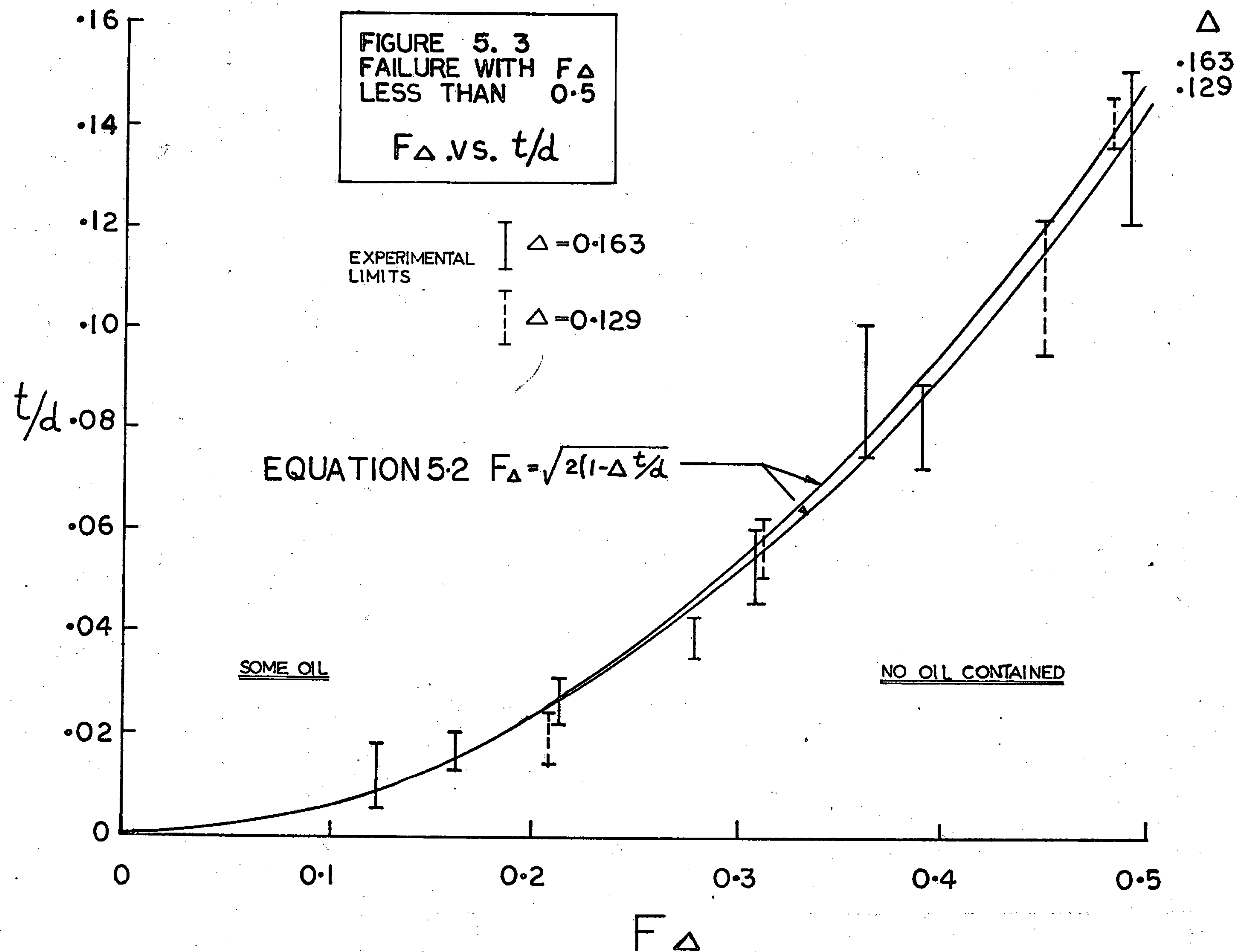


FIGURE 5. 3
FAILURE WITH FΔ
LESS THAN 0·5
FΔ .vs. t/d
EXPERIMENTAL LIMITS
Δ =0·163
Δ =0·129
EQUATION 5·2 FΔ = √2(1-Δ t/d
SOME OIL
NO OIL CONTAINED
Δ
·163
·129
t/d
·16
·14
·12
·10
·08
·06
·04
·02
0
0
0·1
0·2
0·3
0·4
0·5
FΔ

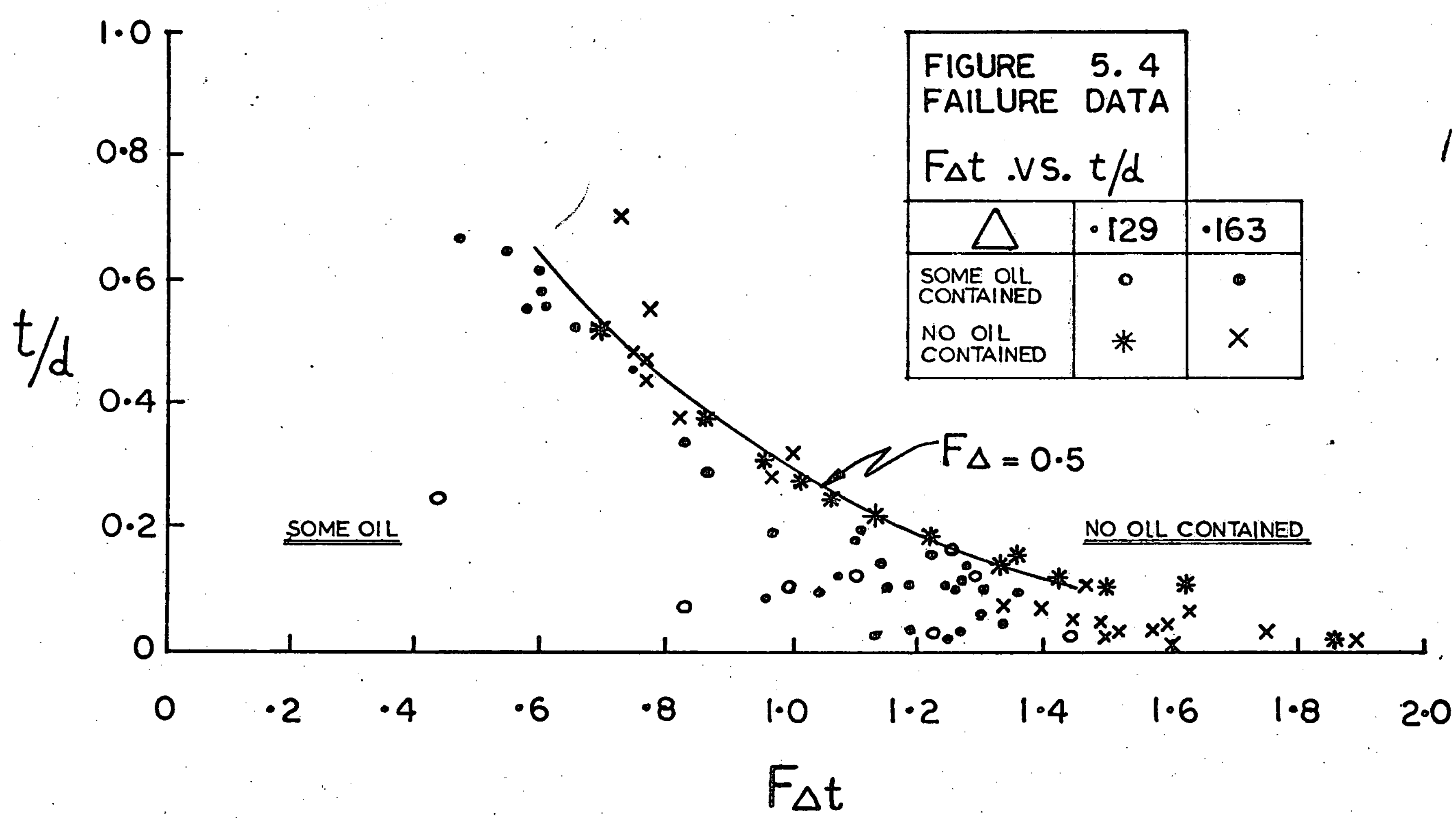


FIGURE 5. 4
FAILURE DATA
FΔt .VS. t/d
Δ
·129
·163
SOME OIL CONTAINED
NO OIL CONTAINED
FΔ = 0·5
SOME OIL
NO OIL CONTAINED
t/d
1·0
0·8
0·6
0·4
0·2
0
·2
·4
·6
·8
1·0
1·2
1·4
1·6
1·8
2·0
FΔt

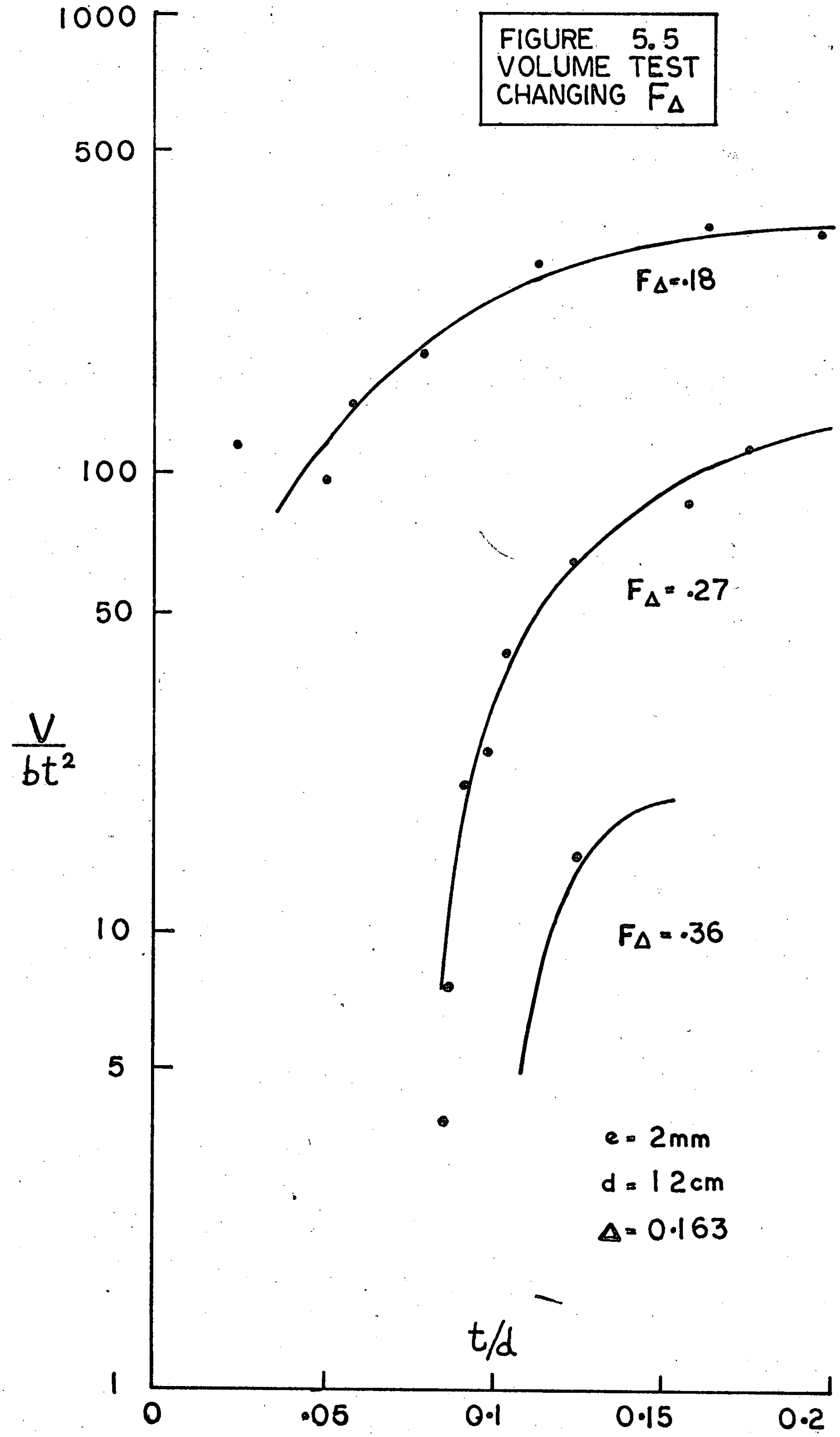


FIGURE 5.5
VOLUME TEST
CHANGING F_Δ
1000
500
100
50
10
5
1
$\frac{V}{bt^2}$
F_Δ = ·18
F_Δ = ·27
F_Δ = ·36
e = 2mm
d = 12cm
Δ = 0·163
t/d
0
·05
0·1
0·15
0·2

The other oils, with $\mu \geq 74$ cP developed no comparable interfacial waves. This plot shows a systematic decrease in containable volume with an increase in oil viscosity. Wilkinson's analysis of the maximum slick (6) shows that the slick profile is dependent on the interfacial fraction factor, f_i. The friction factor, f_i, was estimated from measurements as outlined in Appendix C, and shows some dependence on oil viscosity. It is probable that the parameter μ_o/μ can be fully accounted for by including the interfacial friction factor in the analysis of the slick profile.

In all the tests where interfacial waves did not develop, the minimum value of barrier draft, to which the barrier could be raised in the experiments, was equal to the maximum thickness of the oil slick. The values of V/bt^2 quoted for each t/d value are thus the absolute maximums and are not likely to be equalled in practice. Therefore, when t/d is less than 0.2, the barrier draft simply limits the volume of oil: this is clearly not a form of slick instability such as detailed by Wilkinson (6).

From the curves of Figure (5.5), values of t/d and F_Δ for various values of v/bt^2 were obtained and plotted in Figure (5.8). This plot shows the interpolated lines of constant V/bt^2 in relation to the zero-volume line. This is the preferred method of plotting volume-containable when the relative draft ratio, t/d, is the limiting factor.

Angled Barriers

The equation describing diversion is

$$\sin\theta = \Phi_a (F_\Delta, t/d, f_b, \mu_o/\mu) \qquad (2.8)$$

where θ is the maximum angle at which the barrier can be placed and still have all the oil diverted. Figure (5.9) shows a plot of $\sin\theta$ versus F_Δ with t/d equal 0.1 for two oils with differing density and viscosity. From the results it appears that varying μ_o/μ does not affect the value of θ and therefore the ratio μ_o/μ can he left out of equation (2.8).

Figure (5.10) shows data for constant t/d = 0.3 but for three values of flow depth. The experimental values however all fell on the same line and thus it appears that the friction factor f_b has little effect on θ. Therefore the maximum angle for deflection should depend upon only on F_Δ and

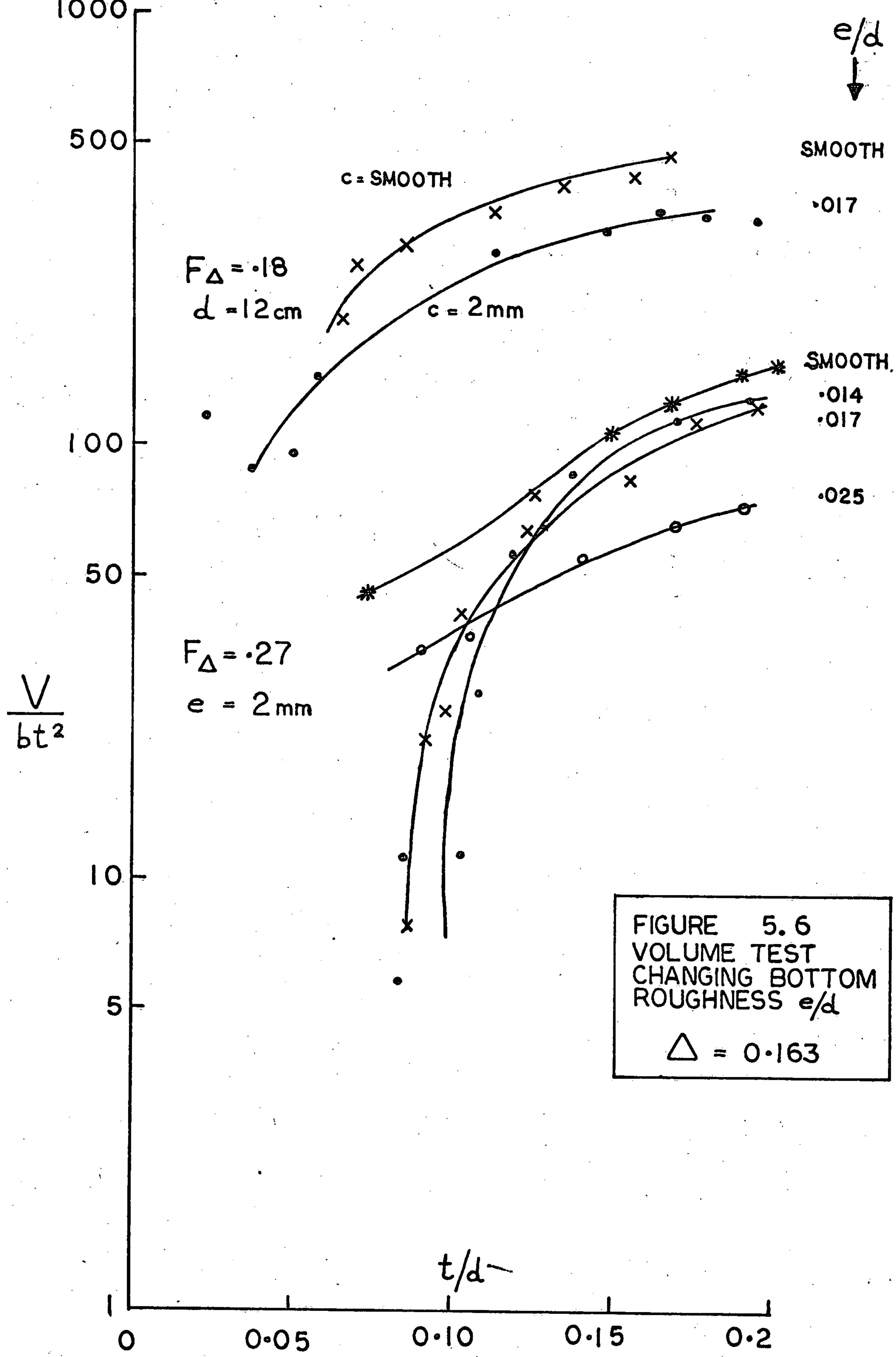


FIGURE 5.6
VOLUME TEST
CHANGING BOTTOM
ROUGHNESS e/d
Δ = 0·163

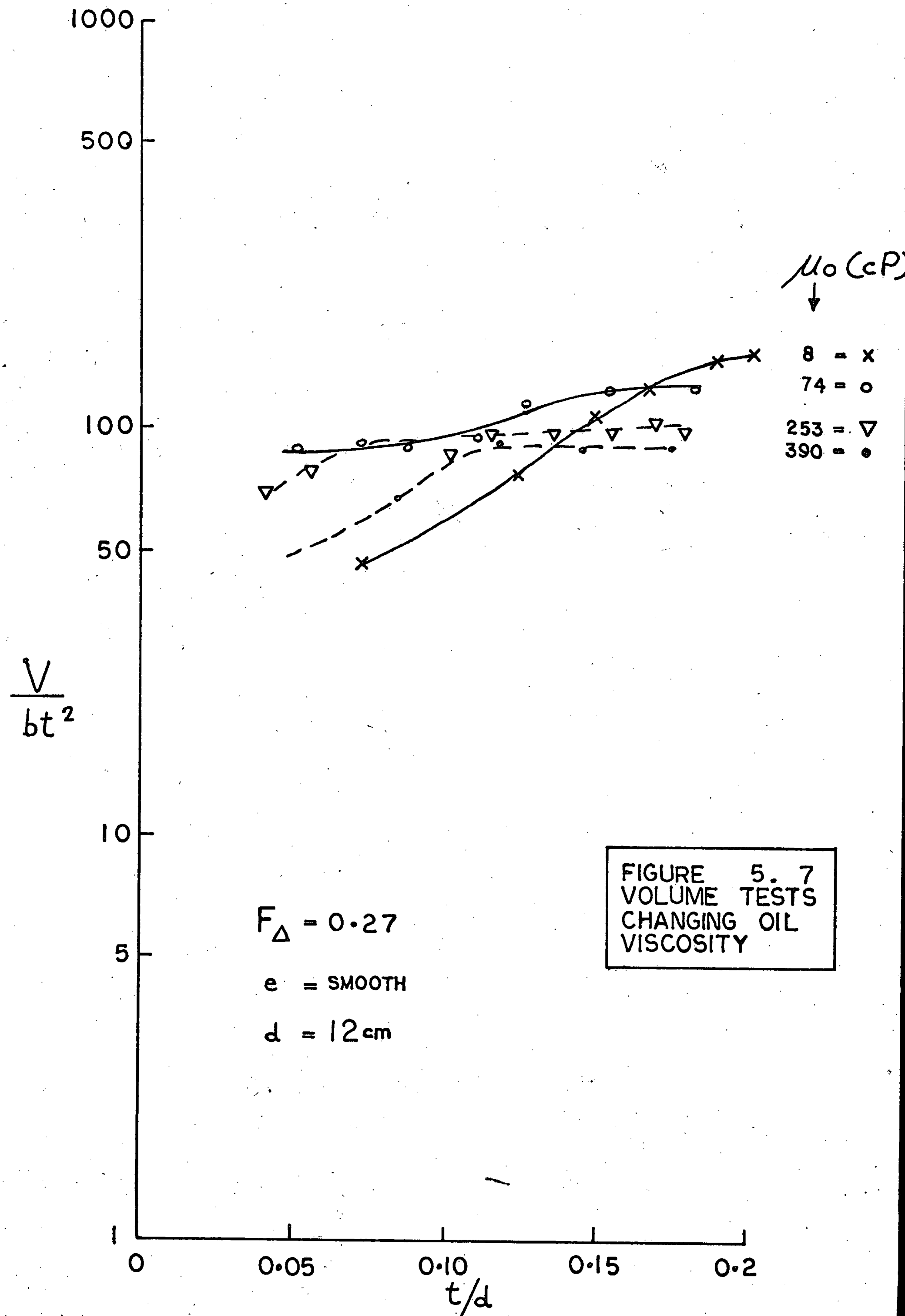


FIGURE 5. 7
VOLUME TESTS
CHANGING OIL
VISCOSITY

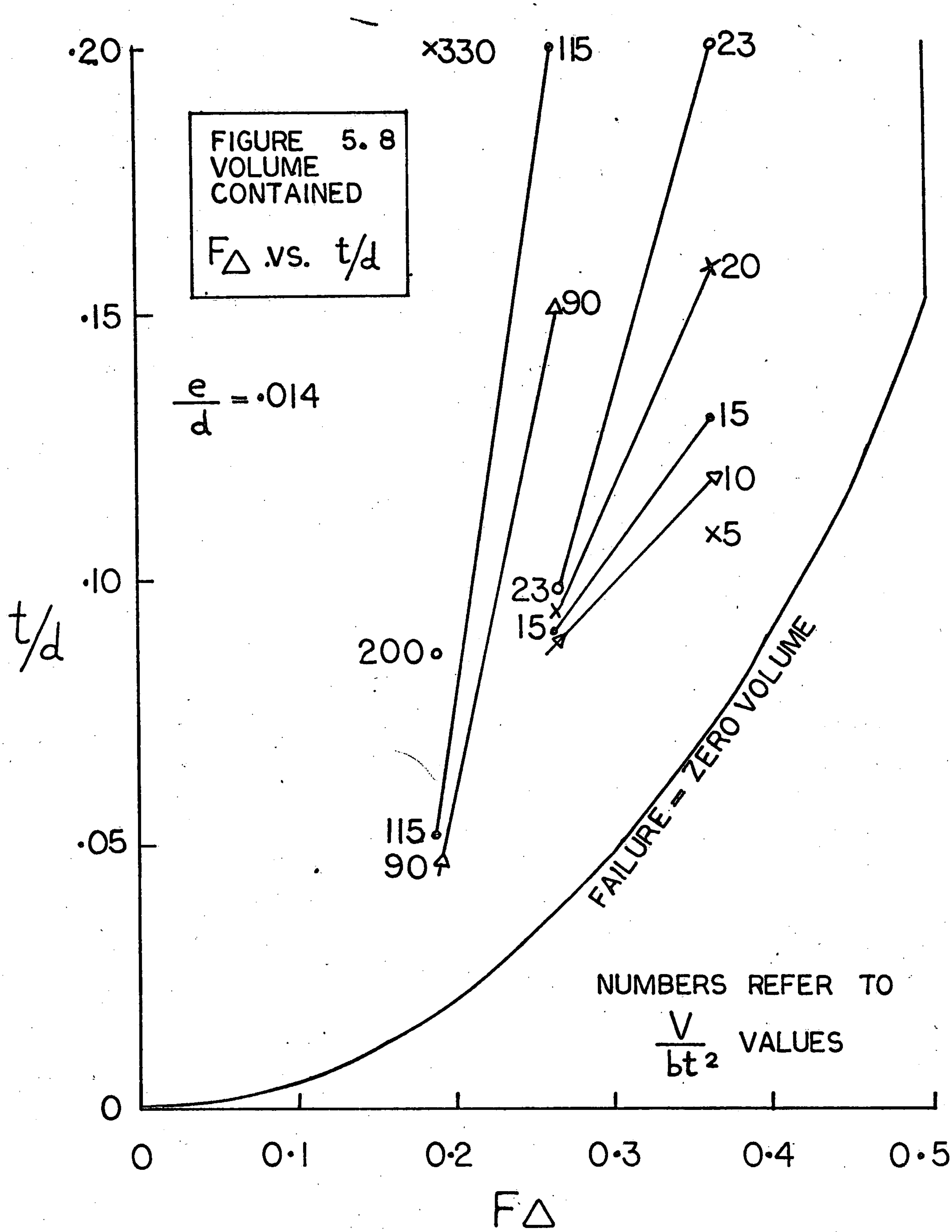


FIGURE 5. 8
VOLUME CONTAINED
F△ vs. t/d
e/d = ·014
t/d
F△
·20
·15
·10
·05
0
0
0·1
0·2
0·3
0·4
0·5
×330
115
23
20
90
15
10
×5
23
15
200
115
90
FAILURE = ZERO VOLUME
NUMBERS REFER TO V/bt² VALUES

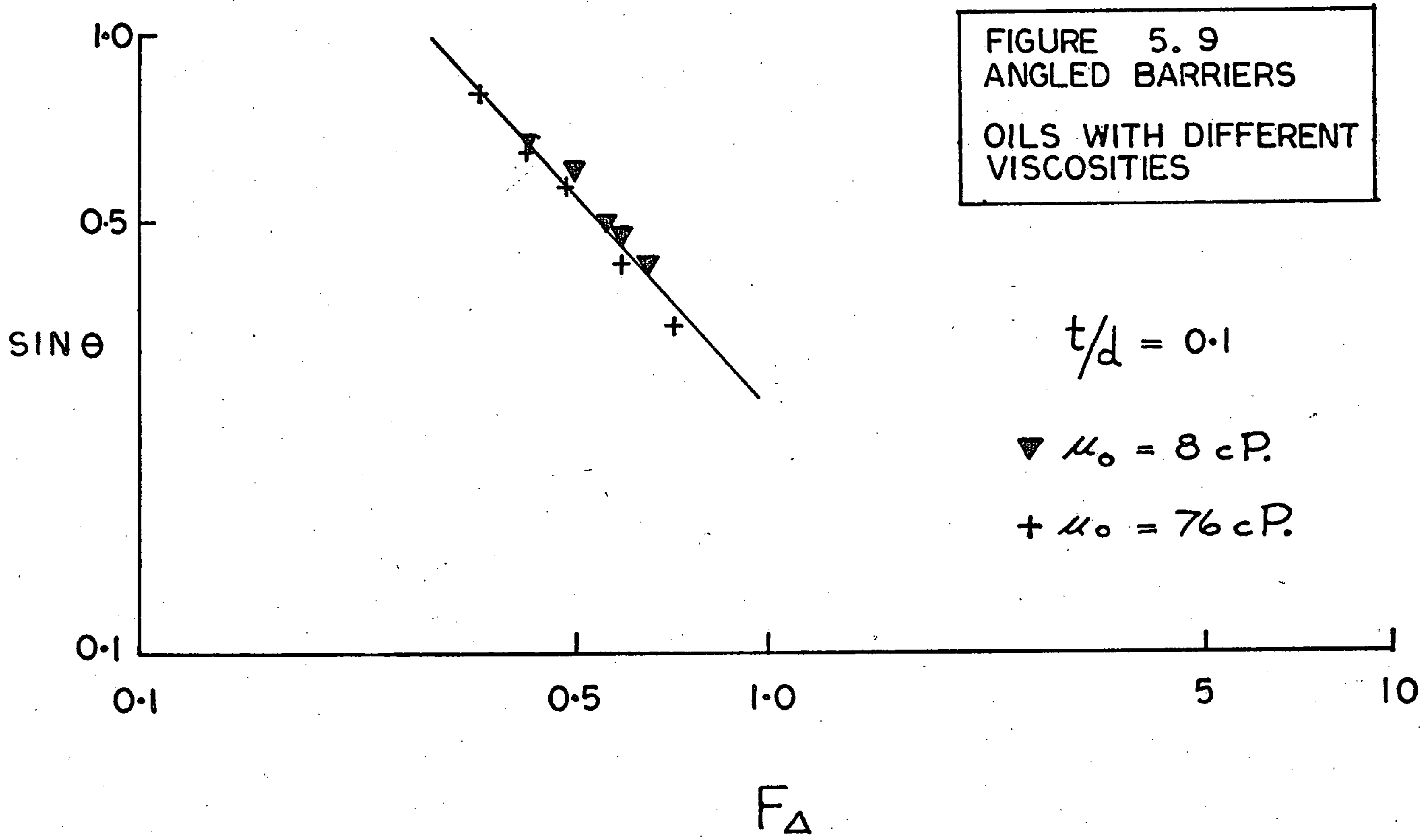


FIGURE 5.9
ANGLED BARRIERS

OILS WITH DIFFERENT VISCOSITIES

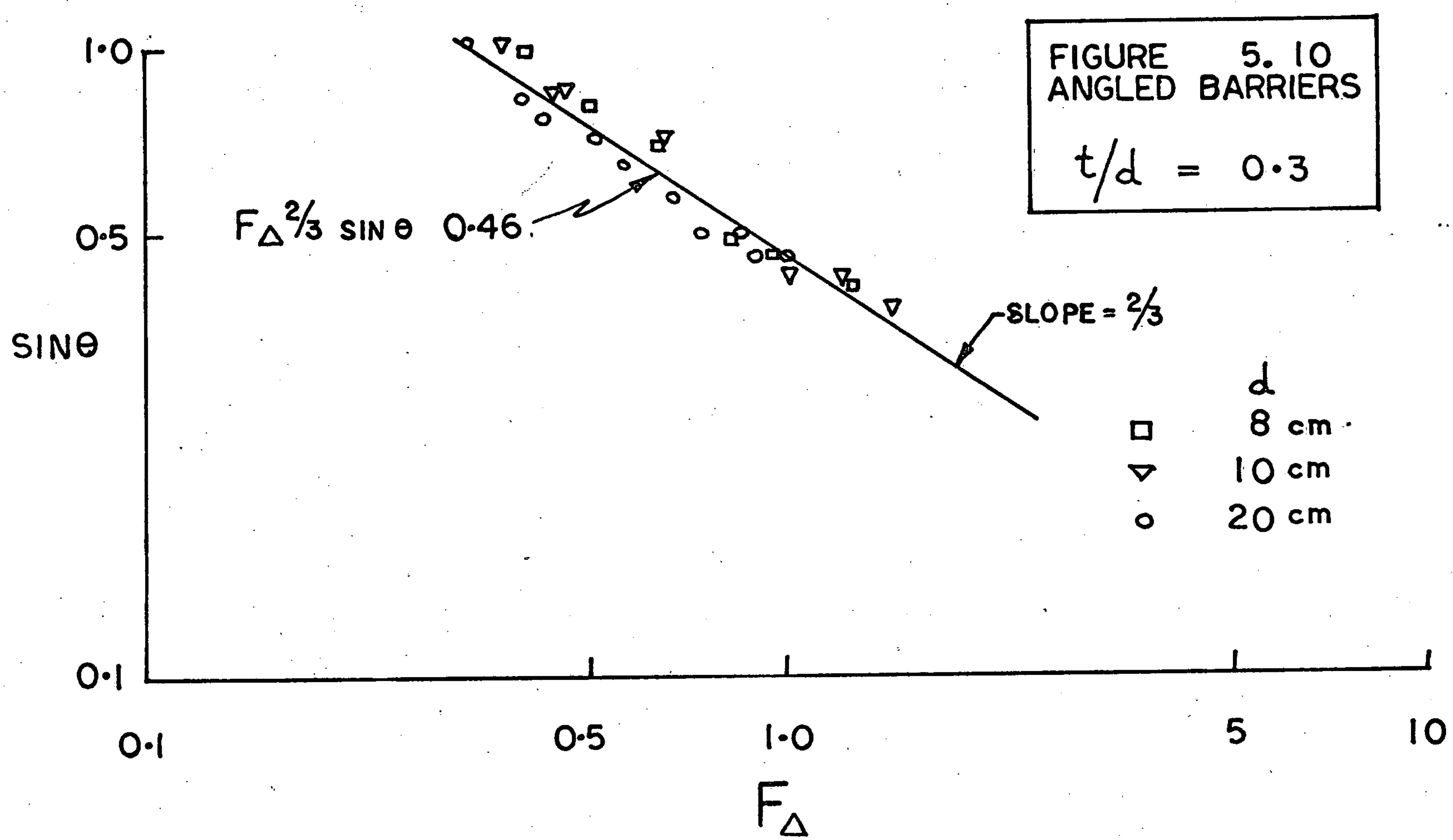


FIGURE 5. 10
ANGLED BARRIERS
t/d = 0·3
1·0
0·5
0·1
SINθ
F△ 2/3 SIN θ 0·46
SLOPE = 2/3
d
8 cm
10 cm
20 cm
0·1
0·5
1·0
5
10
F△

t/d, i.e.

$$\sin\theta = \Phi_a(F_\Delta, t/d) \tag{5.4}$$

the empirical relationship obtained from Figure (5.10) is

$$\sin\theta = 0.46\, F_\Delta^{-2/3} \tag{5.5}$$

In Figure (5.11) data for t/d = 0.1 but for different flow depths are plotted. For the points for d = 20 cm the data follows more or less a - 2/3 power variation similar to the t/d = 0.3 points. However for cases where d = 8 cm and 10 cm the points do not follow such a line but rather show that $\sin\theta \sim F_\Delta^{-1}$. Obviously there is a change in behaviour between the deep and shallow cases.

The flow pattern about an angled barrier is extremely complex. The descriptive analysis consistent with experimental observations is proposed where: when t/d is small the oil forms a headwave behind the barrier whose thickness can exceed the barrier draft. To prevent oil loss the barrier must be at a sufficient angle such that the relative densimetric Froude number is less than that which would generate a headwave whose thickness would exceed the barrier draft. It may be that the difference between the volume of oil arriving at the barrier and the volumme leaving the barrier by being diverted is less than what is required to form a headwave which would "undertop" the barrier. If such is the case another failure mechanism would dominate.

At the flow velocities encountered in the angled-barrier tests, droplets were formed and failure by droplet formation was one failure mechanism in the angled barrier tests.

Therefore at a lower velocities (lower F_Δ) where the rate of diversion is less, the required angle is determined by the need to prevent "undertopping" of the barrier by the moving but retained headwave. This condition is adequately explained by a relation of the form:

$$F_\Delta \sin\theta = \text{constant} = k_H \tag{5.6}$$

At higher velocities (higher F_Δ), the required angle is determined by the

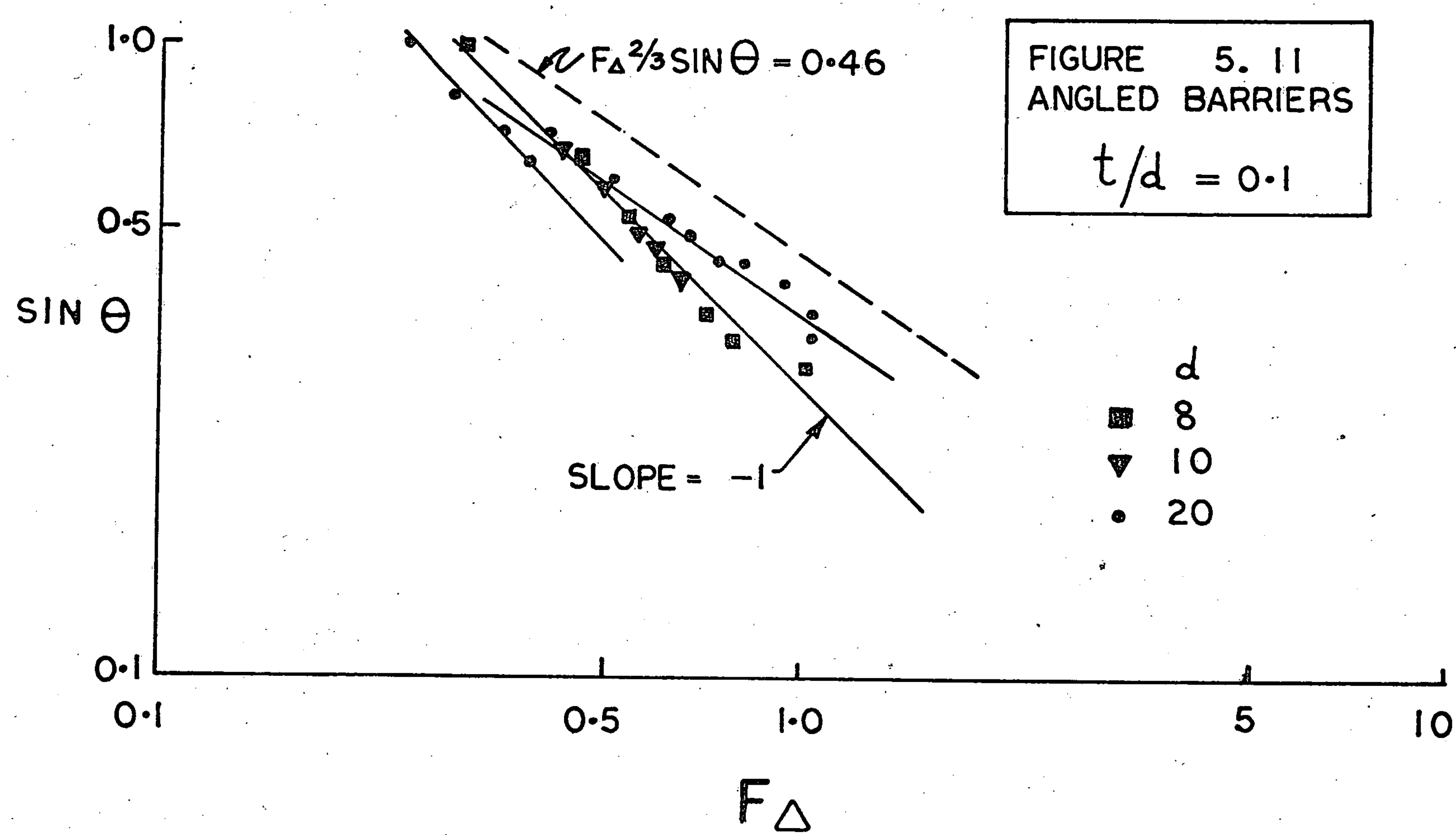


FIGURE 5. 11
ANGLED BARRIERS
t/d = 0·1
1·0
0·5
0·1
SIN θ
0·1
0·5
1·0
5
10
FΔ
FΔ 2/3 SIN θ = 0·46
SLOPE = −1
d
8
10
20

need to keep the relative velocity between the oil and the water below that at which droplets will form. This condition is expressed by the relation

$$F_{\Delta}^{\,2/3} \sin\theta = k_D \qquad (5.7)$$

This requirement appears, from the test data to be a less conservative requirement than that expressed by equation (5.6)

From this test data the values of the constants are:

$$\begin{aligned} k_H &\simeq 0.24 \\ k_D &\simeq 0.46 \end{aligned} \qquad (5.8)$$

The constant k_H is a measure of the rate that the barrier can divert oil in comparison to the rate at which oil arrives at the barrier prior to diversion. Thus the parameters determining this constant will be the viscosity of the oil, the thickness of the slick and the roughness of the barrier material. The ratios μ_o/μ and h/d have been shown to be of negligible importance. The barrier used in these tests was smooth and devoid of joints and projections. A parabolic-in-plan barrier was used in these tests to demonstrate that a curved barrier is adequately modelled in the laboratory by a barrier that is straight in plan as shown by the results of Figure (5.12). This parabolic barrier was also smooth and devoid of joints and projections. This is the optimum condition and provided the prototype is similar the value of 0.24 for k_H probably can be used in the prototype.

The value of k_D is determined by the value of σ as well as the flow geometry. The interfacial tension, σ, was 1.08×10^{-2} N/M for the oil used in these experiments. Further tests are required to show whether this constant varies for other values of σ.

The test data are plotted in Figure (5.13) with $\sin\theta$ plotted against $F_{\Delta t}$. Diversion will be successful for any t/d less than 0.3 if the values of $\sin\theta$ and $F_{\Delta t}$ intersect on the diversion side of the line.

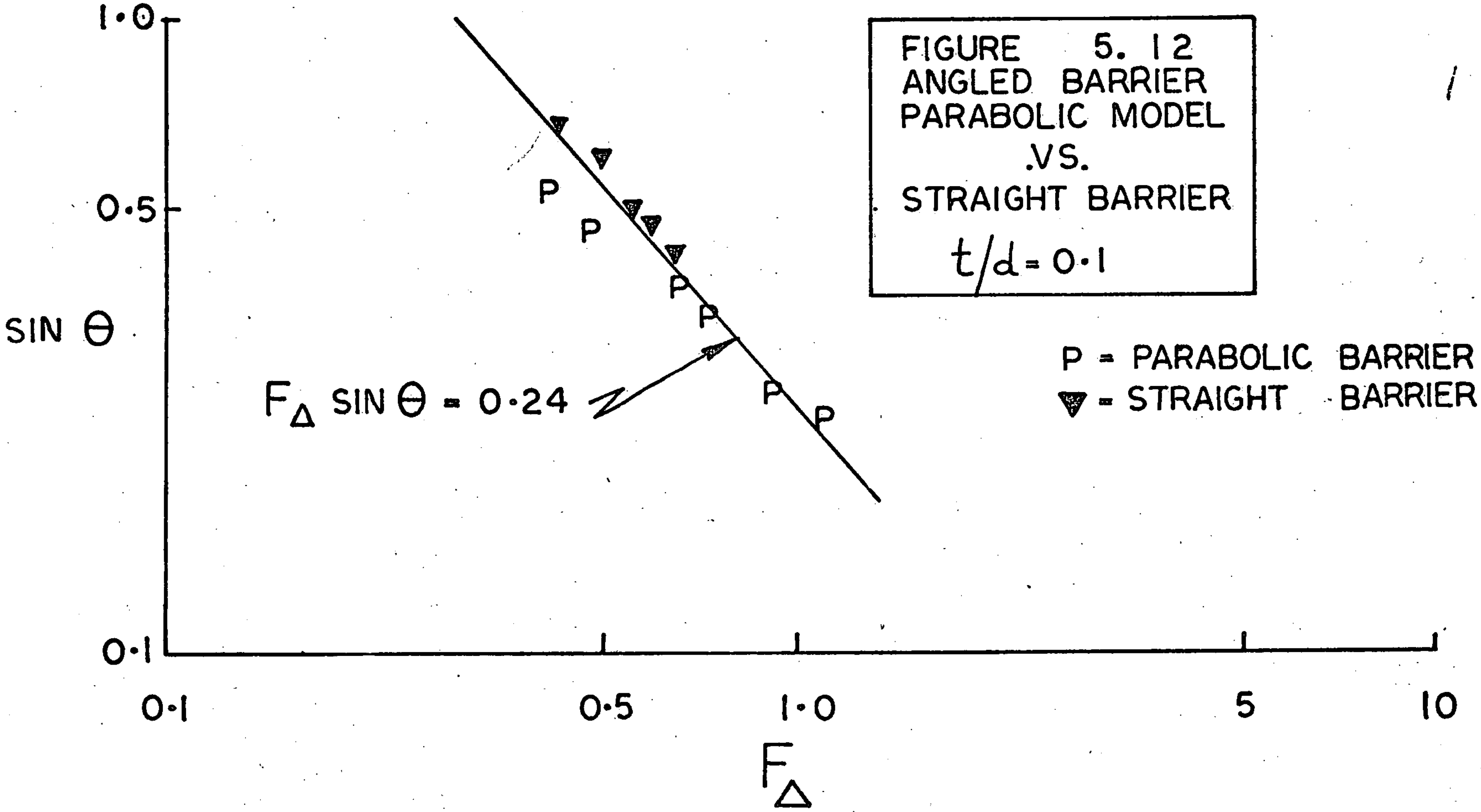


FIGURE 5. 12
ANGLED BARRIER
PARABOLIC MODEL
.VS.
STRAIGHT BARRIER
$t/d = 0 \cdot 1$

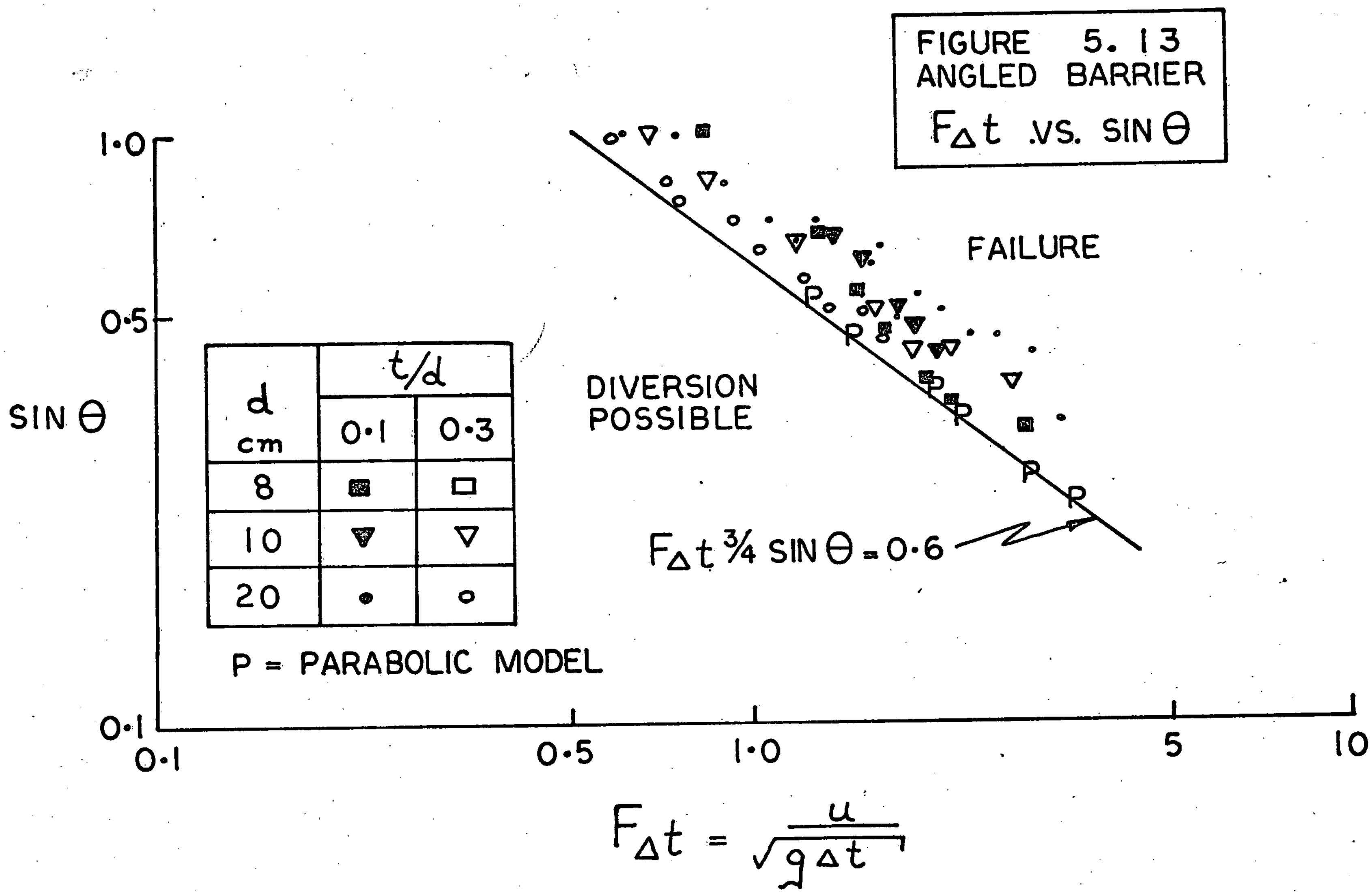


FIGURE 5.13
ANGLED BARRIER
FΔt VS. SIN Θ
1·0
0·5
0·1
SIN Θ
0·1
0·5
1·0
5
10
FAILURE
DIVERSION POSSIBLE
FΔt ¾ SIN Θ = 0·6
d cm
t/d
0·1
0·3
8
10
20
P = PARABOLIC MODEL
FΔt = u/√(gΔt)

6. CONCLUSIONS

1) From the dimensional analysis of this report, the significant parameters needed to describe oil containment and diversion are:

i) $F_{\Delta} = u/\sqrt{g\Delta d}$, the densimetric Froude number based on the depth of the flow.

ii) t/d, the barrier relative draft.

iii) f_b, the flow friction factor

iv) $\sqrt{u^2 d\rho/\sigma}$, the flow Weber number.

2) Failure of the barrier to hold any oil will occur when any of the three inequalities below is satisfied.

a) $F_{\Delta} = u/\sqrt{g\Delta d} > 0.5$ 6.1

b) $F_{\Delta} > \sqrt{2(t/d)}$ or $F_{\Delta t} > \sqrt{2}$ 6.2

c) $F_{\Delta} \cdot \sqrt{\frac{u^2 d\rho}{\sigma}} > k$ 6.3

where k varies from 11.0 to 28.0, from test data.

3) Estimates of volume containable, when t/d is less than 0.2, can be obtained from the graphs of V/bt^2 versus t/d and F_{Δ}, in Sections 4 and 5 of this report.

4) Guidelines for the angle of the barrier to the flow for complete diversion are shown in Figure 5.11 and by the inequalities:

$$F_{\Delta} \sin\theta < k_H \quad (6.4)$$

$$F_{\Delta}^{2/3} \sin\theta < k_D \quad (6.5)$$

Equation 6.4 is the more conservative relation and applies in the case where there is sufficient oil moving but contained to form a headwave of sufficient size to "undertop" the barrier. Tentative values of k_H equal 0.24 and k_D equal 0.46 have been experimentally determined.

Further Work

From the analysis of the test results of this program the following suggestions are made:

1) It would be useful, but not essential to generate more data to complete the curves of constant V/bt^2 on a plot of F_Δ versus t/d, and to show how f_b influences the volume contained at various values of F_Δ.

2) It would be useful if a method could be found to chemically increase, as an additive to the slick, the value of the interfacial surface tension of the oil, σ, when containment is necessary in flows where the flow velocity is greater than about 18 centimeters per second at the free surface.

3) The influence of σ on the angled barrier constant k_D should be experimentally determined, and in conjunction, the value of k should be determined for a range of densimetric Froude number, F_Δ.

4) The optimum t/d ratio for angled barriers should be determined experimentally so that the equation:

$$F_\Delta^{2/3} \sin\theta < k_D$$

would apply in all cases. This would allow the use of high diversion angles and hence less barrier length resulting in a cost reduction and time saving at a spill site.

The behaviour of a free slick in a riverflow has not been studied. It has been reported that, on a river with a large relative roughness, e/d and large Reynolds number, R_e, an entire slick disappeared in a "rough" section of the river and reappeared downstream in a "quiet" section. This "emulsification" has not been reported in the literature and was not noted in this laboratory program, where e/d and R_e were both relatively small. It is crucial that an understanding of this mechanism be acquired.

There is some debate as to where a free slick would be located across the flow on the surface, some time and some distance downstream after the spill. It may be that the slick will spread in a viscous fashion to the shore, continuously with downstream motion, with the result that most of the slick will wash up on the shore on a long river, or it may be that the slick will show a "negative viscosity" effect and remain in the centre, high velocity region of the flow. In the latter case it will be useless to to place the barriers only a small fraction of the width of the river from the shore.

6) Therefore it is recommended that the behaviour of a free slick on a river be experimentally studied.

APPENDICES

Appendix A

Theories Reviewed by

Lau and Kirchheffer (1)

APPENDIX A

Theories of Oil Containment

Reviewed by

Lau and Kirchheffer

Benjamin, T.B., "Gravity Currents and Related Phenomena", Journal of Fluid Mechanics, Vol. 31, Part 2, 1968, pp 209-248.

Christianson, R.M., and Hixson, A.N., Ind. and Eng. Chem. 49, 1957, pp. 1017-24.

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.

Hinze, J.O., "Fundamentals of the Hydrodynamic Mechanism of Splitting up in Dispersion Processes", A.I.Ch.E. Jour., 1, 1955, pp. 289.

Jones, W.T., "Instability at an Interface Between Oil and Flowing Water", Trans. ASME, Vol. 94, Dec., 1972, pp. 874-878.

Robbins, R. J., "The Oil Boom in a Current", thesis presented to M.I.T., Department of Electrical Engineering, at Cambridge, Mass., in 1970, in partial fulfillment of the requirements for the degree of Master of Science.

Wicks, M., III, "Fluid Dynamics of Floating Oil Containment by Mechanical Barriers in the Presence of Water Currents", Proceedings API/FWPCA Joint Conference on Prevention and Control of Oil Spills, New York, December 15-17, 1969, pp. 55-106.

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.

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.

Appendix B

Estimates of Bottom Friction Factors

Bottom Friction Factor, f_b

The flume slopes required to develop uniform flow for these experiments was extremely small, too small to give sufficiently reliable results for f_b. The friction factor, therefore, was calculated from the relation derived from the logarithmic velocity distribution:

$$f_b = \frac{8}{(2.5 \ln (0.368d/k_s) + B)^2}$$

where k_s = equivalent sand grain roughness

B = constant in logarithmic velocity distribution and for rough turbulent flow equal to 8.5.

The values of f_b for the lines plotted in Figure (5.5) are tabulated in Table B.1. Because the sand was always placed such that a uniform, closely packed layer was obtained, it was felt that k_s can be taken equal to e.

Table B.1. Values of f_b

e cm	d cm	$\frac{e}{d}$	f_b
0.2	7.9	.025	.035
0.2	12.	.017	.030
0.2	14.5	.014	.029
0.1	12.2	.008	.025

Appendix C

Estimates of the Interfacial Friction Factor f_i

Interfacial Friction Factor

Estimates of the interfacial friction factor are usually determined from measurements of the profile of a contained slick, by means of some analytically derived equation. Inaccuracies in the estimates of f_i arise from mistakes made in deriving the equation or a lack of precision in the experimental measurements.

In these experiments the oil-water interface was profiled using electronic point gauge which was sensitive to a conducting fluid. Since the oil used was essentially a perfect insulator, as determined in the calibration, the point gauge followed the interface to ± 0.2 millimeter. The output was a chart recorder operating at a 5 times magnification. The servo-system was sufficiently fast to detect interfacial waves.

Profile plots are shown as Figures C.1 to C.7. The estimates of f_i were calculated from the corrected Hoult expression (1):

$$f_i = \frac{(1 - \Delta)\ \Delta\ g}{u^2} \ \frac{h^2}{x}$$

The estimates are tabulated in Table (C.1)

Table C.1 Estimates of f_i

Test Number (volume series)	F_Δ	Δ	μ_o cps.	f_i
17	.267	.163	8	.0111
				.00916
				.00768
				.0130
18	.267	.163	8	.0136
				.00912
				.0108
21	.268	.163	8	.00863
22	.269	.163	8	.00568
				.00262
23	.269	.163	8	.00594
				.00860
111	.270	.097	253	.0140
				.0102
123	.271	.085	390	.0179
				.0224

This data agrees with other published values of f_i, but shows that f_i appears to increase with μ_o/μ.

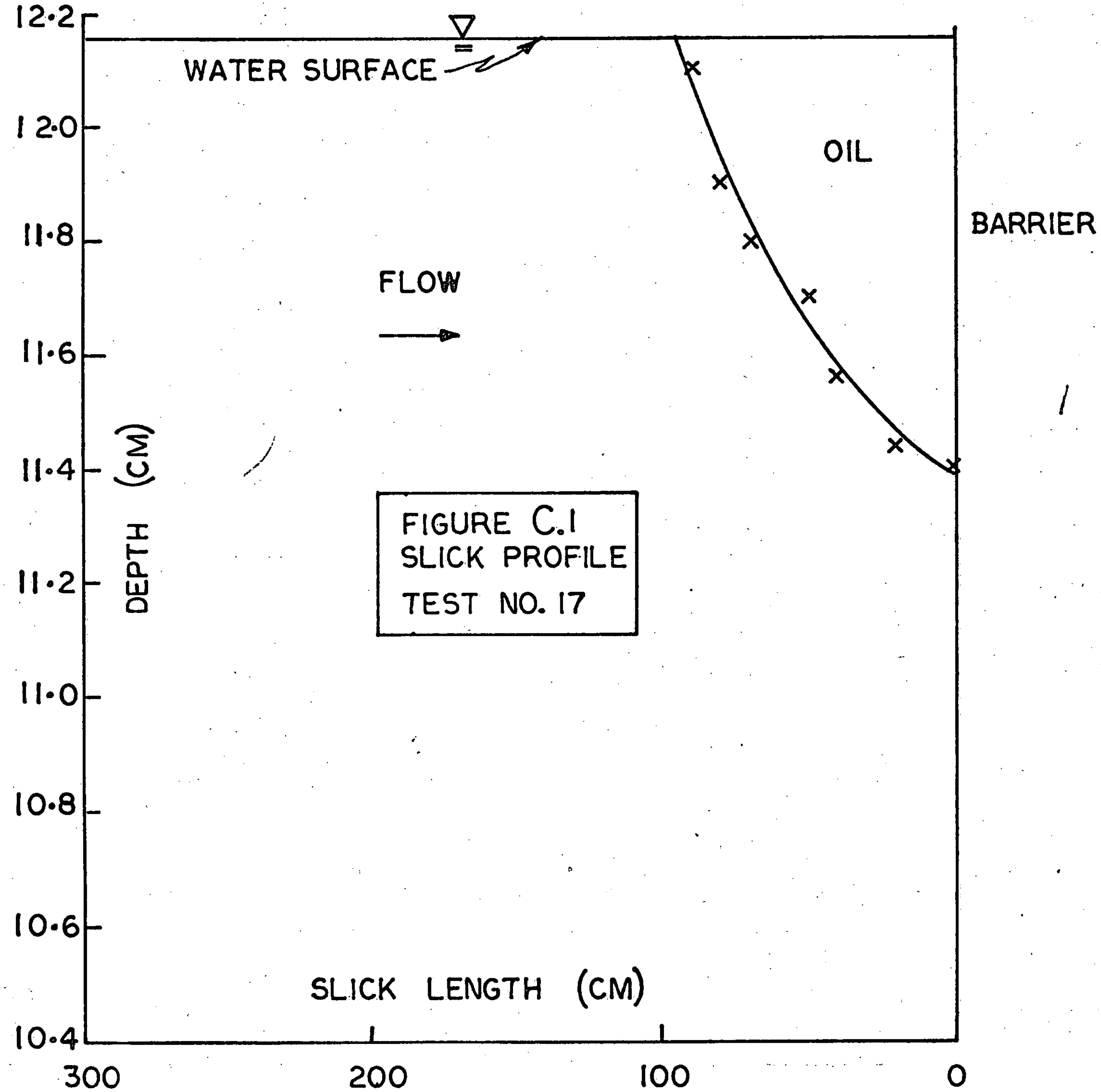


FIGURE C.1
SLICK PROFILE
TEST NO. 17

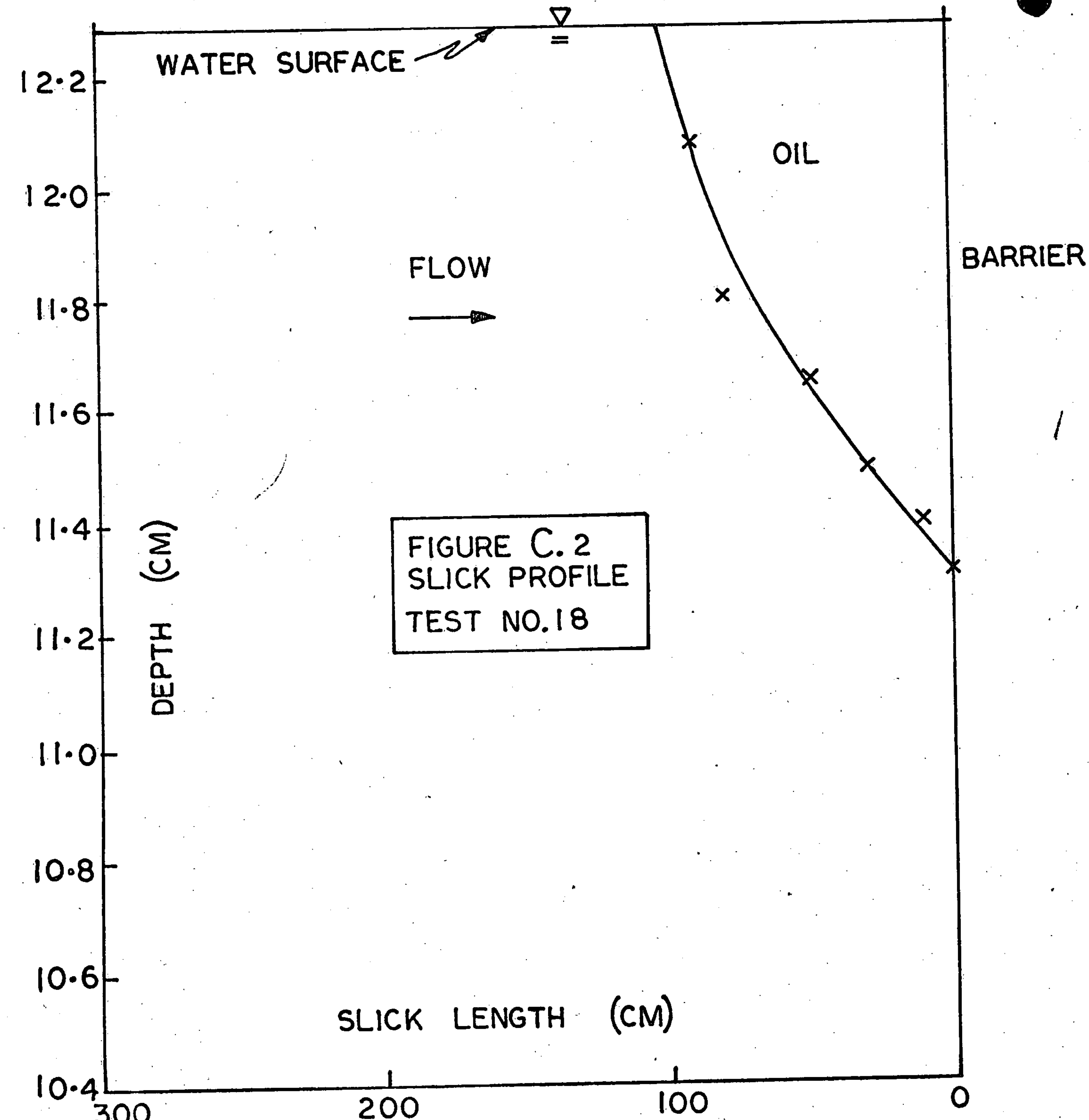


FIGURE C.2
SLICK PROFILE
TEST NO.18

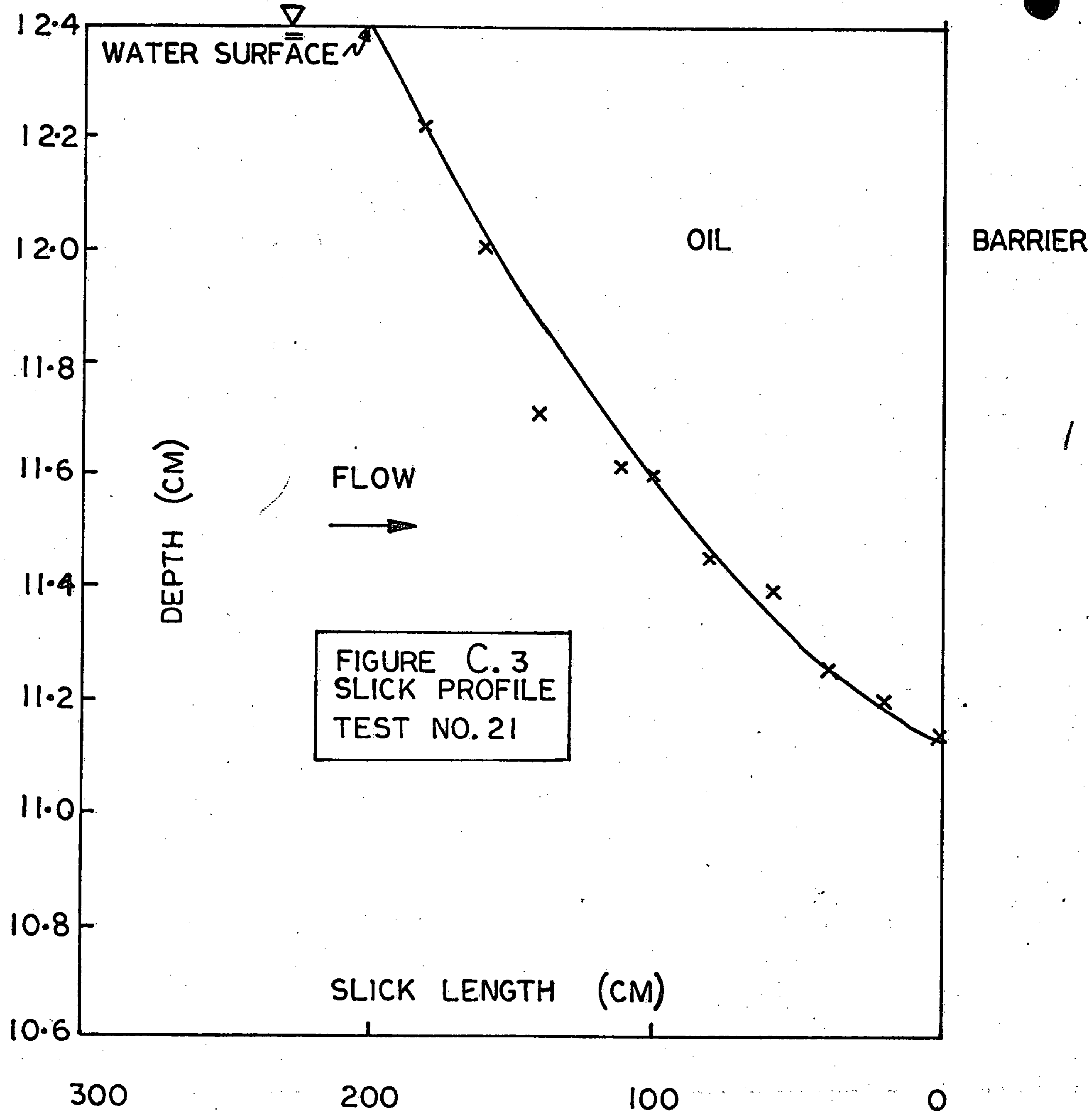


FIGURE C.3
SLICK PROFILE
TEST NO. 21

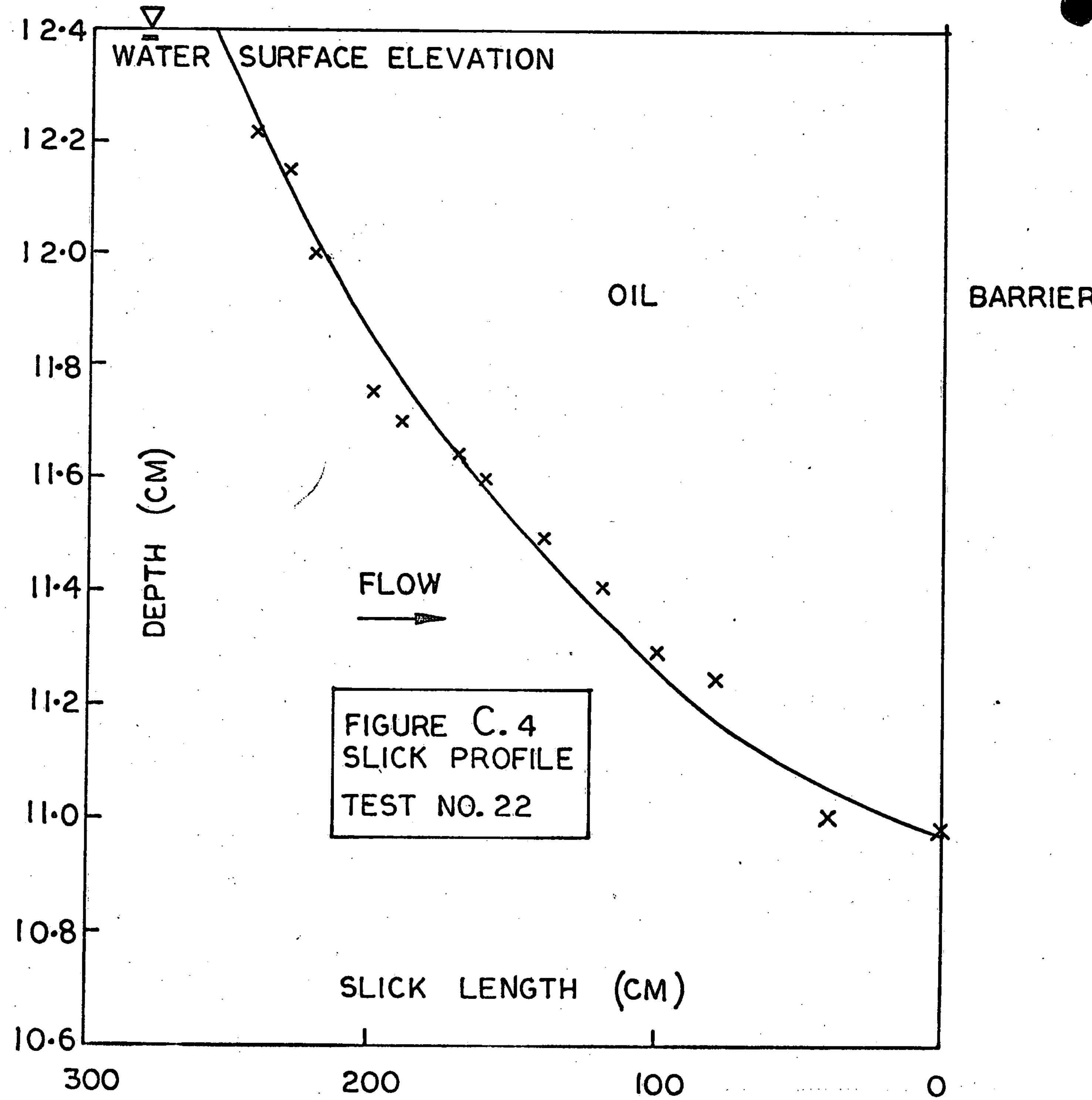


FIGURE C. 4
SLICK PROFILE
TEST NO. 22

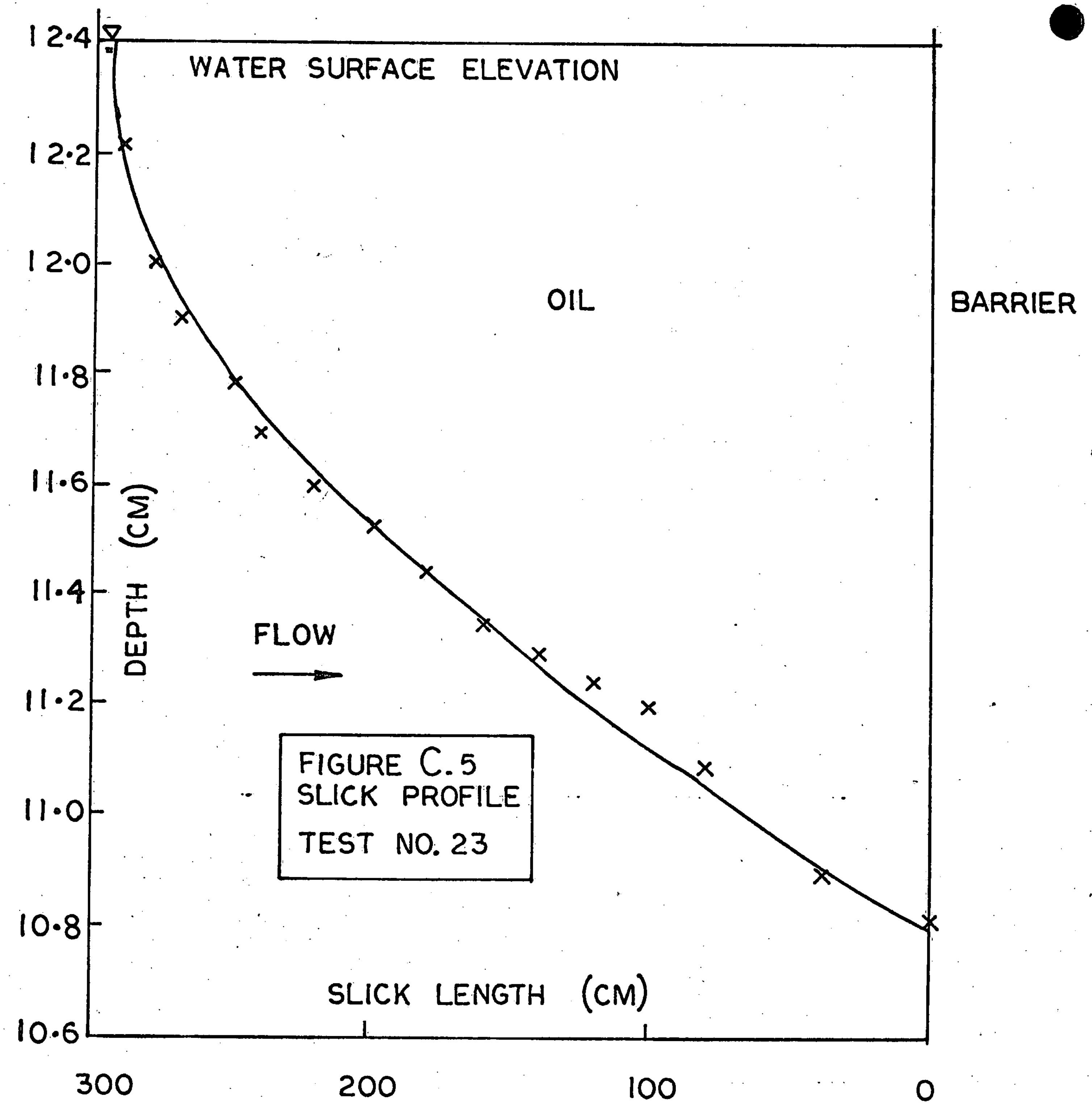
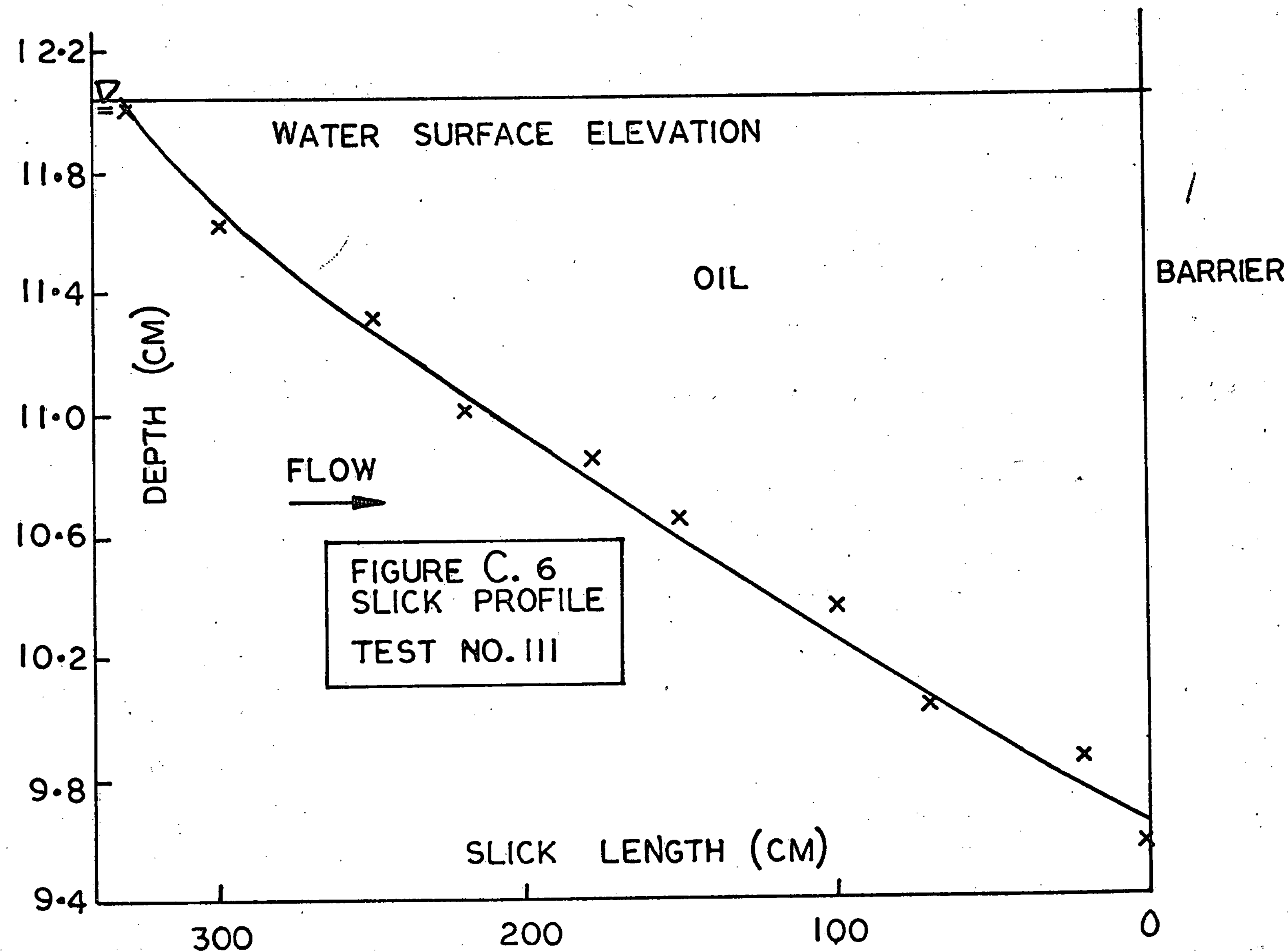


FIGURE C.5
SLICK PROFILE
TEST NO. 23


12·2
11·8
11·4
11·0
10·6
10·2
9·8
9·4
DEPTH (CM)
WATER SURFACE ELEVATION
OIL
BARRIER
FLOW
FIGURE C. 6
SLICK PROFILE
TEST NO. 111
SLICK LENGTH (CM)
300
200
100
0

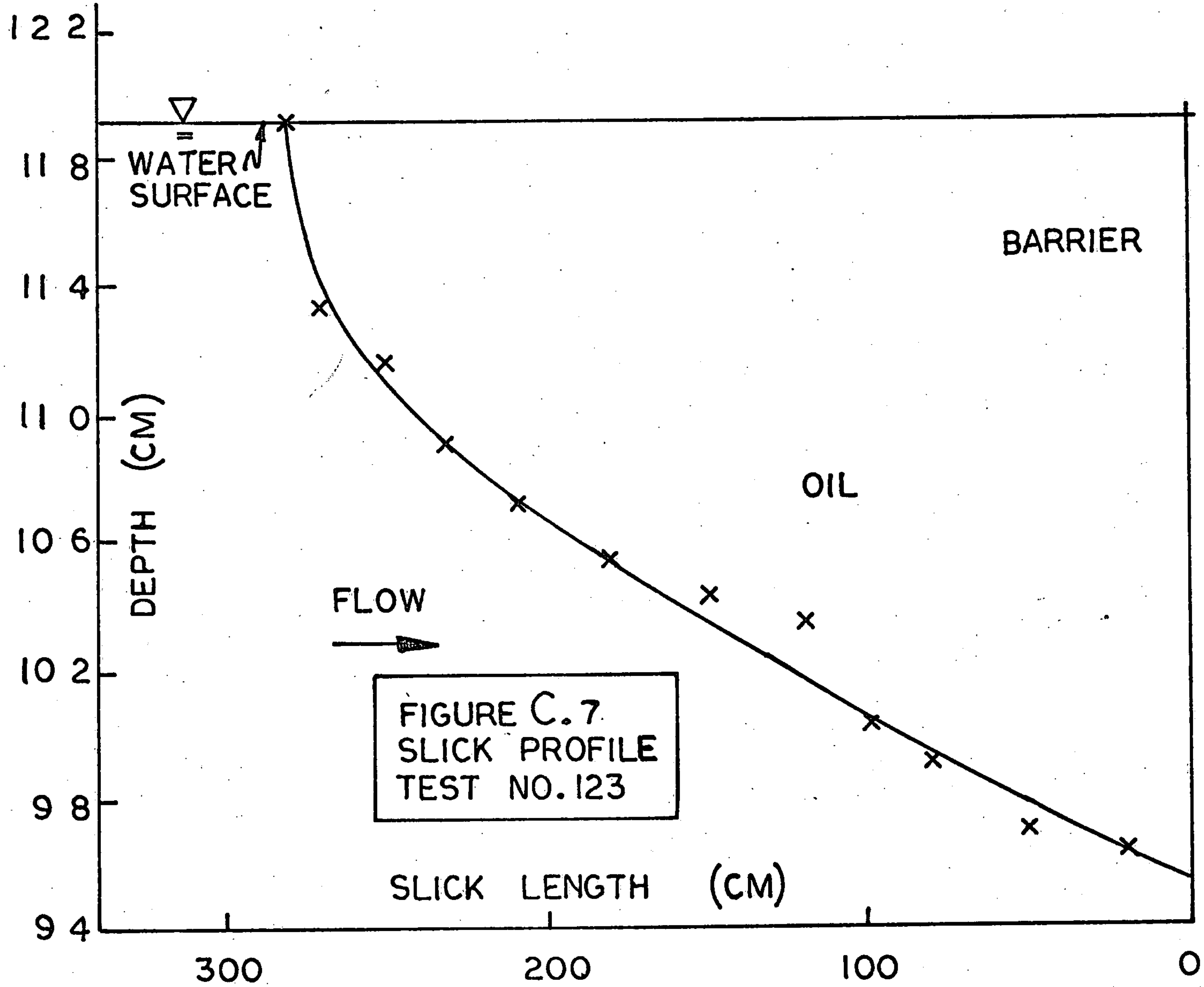


FIGURE C.7
SLICK PROFILE
TEST NO. 123

Appendix D

Droplet Formation

APPENDIX D

Droplets:

Much has been written (3,4,11,12) about the formation and entrainment of droplets into the flow, yet a theoretical model which fully and accurately predicts losses from the contained slick in this manner has not yet been developed. What is lacking is a basic understanding of what governs the return of an oil droplet to the slick. Therefore, for practical purposes at the present, it is imperative that containment and diversion conditions be such that droplets are not formed. This condition is governed by an equation similar to (2.4)

$$F_\Delta \cdot \sqrt{\frac{u^2 d\rho}{\sigma}} = k$$

Where k is some numerical constant. The value of this constant has been determined experimentally for "significant droplet formation" by Hale et al to be 28. Lindemuth gives values as in Table (D.1).

Table D.1. Droplet Formantion Constant Lindemuth Data

$\sqrt{\frac{u^2 d\rho}{\sigma}}$	F_Δ	k
59.7	.401	23.9
45.0	.401	18.0
130.	.219	28.5
48.6	.356	17.3

The writer determined that the constant has a value of 11.0 when F_Δ is 0.438 and $\sqrt{u^2 d\rho/\sigma}$ is 25.1. A theoretical value is 7.0. Flow velocities at which droplet formation may be expected are tabulated in Table (D.2), for a "typical" case and an "optimistic" case.

Table D.2

Case	Δ	σ dynes/cm	k	u cm/sec
Typical	0.1	10	10	18
Optimistic	0.17	25	28	43

For diversion, the relative velocity between the oil and the flow must be less than 18 to 43 cemtimeters per second, and for containment the flow speed must be less than 18 to 43 centimeters per second, or droplets will be formed.

It is apparent that it would be useful if the value of interfacial surface tension, σ, could be chemically increased when containment is required in some flows.

Appendix E

Tabulated Test Results

Table E.1. Failure Series

#	Q cfs	t cm	d cm	t/d	Fail or No Fail	$F_{\Delta t}$	F_{Δ}
1	.197	1.18	6.08	.194	N	1.11	.491
2		0.98	6.08	.161	N	1.22-	.491
3		0.73	6.03	.121	F	1.43	.493
4		2.06	6.16	.334	N	.832	.481
5	.157	.72	5.92	.121	N	1.17	.407
6		.62	5.92	.105	N	1.26	.406
7		.37	5.92	.063	F	1.63	.409
8	.301	4.42	7.37	.600	F	.726	.562
9	.272	3.81	6.81	.559	F	.766	.573
10		4.78	7.38	.648	N	.546	.507
11	.237	3.08	6.58	.468	F	.766	.524
12		4.38	7.08	.619	N	.597	.470
13	.214	3.89	6.79	.573	N	.598	.452
14		3.74	6.74	.555	N	.614	.457
15		3.44	6.59	.522	N	.653	.471
16		2.74	6.29	.436	F	.765	.505
17	.188	3.55	6.50	.546	N	.575	.425
18		4.62	6.92	.668	N	.471	.385
19		1.77	6.07	.292	N	.869	.469
20		1.13	5.98	.189	N	1.10	.479
21		0.83	5.98	.139	N	1.28	.479
22		.63	5.98	.105	F	1.47	.479
23	.232	1.96	6.16	.318	F	1.00	.564
24		3.14	6.54	.480	F	.745	.517
25	.208	2.82	6.22	.453	N	.744	.501
26		1.71	6.11	.280	F	.956	.506
27		2.34	6.24	.375	F	.817	.500
28	0.175	1.18	6.18	.191	N	.971	.423
29		.86	6.16	.141	N	1.144	.427
30		.66	6.16	.107	N	1.305	.427
31		.50	6.15	.081	F	1.50	.427

Table E.1 - Cont'd......... Failure Series

Test #	Q cfs	t cm	d cm	t/d	Fail or No Fail	$F_{\Delta t}$	F_{Δ}
32	.431	3.01	14.97	.200	N	.620	.278
33		1.26	14.96	.084	N	.958	.278
34		0.65	14.95	.0435	N	1.33	.278
35		0.52	14.95	.0348	N	1.49	.278
36		0.47	14.96	.0314	F	1.57	.278
37	.495	1.41	15.01	.094	N	1.04	.319
38		.90	15.00	.060	N	1.30	.319
39		.60	15.00	.040	N	1.59	.319
40		.50	15.00	.033	F	1.75	.319
41	.569	1.52	15.02	.101	N	1.15	.365
42		1.03	15.03	.069	F	1.39	.365
43		1.13	15.03	.075	F	1.33	.365
44	.494	1.17	15.07	.078	N	1.13	.315
45	.615	1.63	15.14	.108	N	1.19	.390
46		1.49	15.12	.099	N	1.24	.390
47		1.34	15.12	.089	N	1.31	.390
48		1.11	15.12	.073	F	1.44	.390
49	.670	1.49	15.04	.099	F	1.36	.429
50		1.71	15.12	.113	F	1.27	.427
51		1.92	15.14	.127	N	1.20	.427
52	.495	.70	15.00	.047	F	1.47	.319
53	.429	.50	14.98	.033	F	1.51	.276
54	.421	.78	20.02	.039	N	.888	.175
55		.48	20.02	.024	N	1.133	.175
56		.40		.020	N	1.24	.175
57		.24		.012	F	1.60	
58	.534	.28	19.92	.014	F	1.89	.224
59		.70	20.06	.035	N	1.19	.223
60		.63	20.07	.031	N	1.26	.223
61		.45	20.04	.022	F	1.49	.223
62	.272	.80	19.00	.042	N	.598	.123
63		.49	19.00	.026	N	.764	.123
64		.35	19.00	.018	N	.904	.123
65		.09	19.00	.005	F	1.78	.123

Table E.1 - Cont'd.........Failure Series

Test #	Q cfs	t cm	d cm	t/d	Fail or No Fail	$F_{\Delta t}$	F_{Δ}
66	.623	1.19	14.97	.079	F	1.60	.450
67		.87	14.97	.058	F	1.87	.450
68		1.04	14.97	.069	F	1.71	.450
69		1.20	14.97	.080	F	1.59	.450
70		1.82	14.97	.122	N	1.29	.450
71	.617	1.42	14.93	.095	F	1.46	.450
72	.684	1.45	15.00	.097	F	1.59	.493
73		1.80	15.00	.120	F	1.42	.493
74		2.05	15.00	.137	F	1.33	.493
75		2.34	15.00	.156	N	1.25	.493
76	.751	1.64	15.08	.109	F	1.62	.535
77		2.38	15.12	.157	F	1.35	.534
78		3.78	15.18	.249	F	1.07	.533
79		5.86	15.52	.378	F	.858	.527
80		4.76	15.36	.310	F	.952	.530
81		4.23	15.28	.277	F	1.01	.532
82		3.40	15.16	.224	F	1.13	.533
83		.94	15.00	.063	F	2.14	
84		8.21	16.24	.506	F	.683	.485
85	.708	3.03	15.07	.201	F	1.13	.507
86		3.44	15.13	.227	F	1.06	.507
87	.314	3.83	15.52	.247	N	.433	.215
88		1.07	15.48	.069	N	.823	.216
89		.49	15.46	.032	N	1.22	.217
90		.35	15.46	.023	N	1.44	.217
91		.21	15.46	.014	F	1.86	.217
92	.449	1.58	15.05	.105	N	.994	.322
93		.93	15.05	.062	N	1.30	.322
94		.76	15.05	.050	F	1.44	.322
95	.553	1.88	15.38	.122	N	1.10	.385
96		1.23	15.38	.080	N	1.36	.385
97		1.06	15.38	.069	F	1.47	.385

Table E.2. Volume Series Cont'd.............

Test	Q cfs	d cm	$\frac{u}{\sqrt{g d \Delta}}$	R cm	t cm	t/d	V cc	$\frac{V}{bt^2}$
57	.297	11.97	.268	10.81	1.16	.097	2000	24.8
58		11.98		10.69	1.29	.108	4000	40.1
59		11.97		10.51	1.46	.122	8000	62.6
60		11.97		10.10	1.87	.156	18000	85.8
61		11.97		9.87	2.10	.175	30000	113.4
62		11.98		9.65	2.33	.194	40000	122.8
63		11.97		10.88	1.09	.091	1500	21.0
64		11.97		10.94	1.03	.086	500	7.85
65	.398	14.44	.271	13.23	1.21	.084	500	5.7
66		14.44		12.97	1.47	.102	1500	11.6
67		14.45		12.90	1.55	.107	4000	27.7
68		14.45		12.74	1.71	.118	10000	57.0
69		14.45		12.48	1.97	.136	20000	85.9
70		14.48		12.04	2.44	.169	40000	112.0
71		14.48		11.70	2.78	.192	60000	129.4
72		14.94		13.24	1.20	.083	1000	11.6
73	.197	12.02	.176	11.43	0.59	.049	2000	95.8
74		12.02		11.59	0.43	.036	1000	90.1
75		12.02		11.75	0.27	.022	500	114.3
76		12.01		11.32	0.69	.057	4000	140.0
77		12.04		11.09	0.95	.079	10000	185.
78		12.05		10.70	1.35	.112	30000	274.
79		12.06		10.28	1.78	.148	58200	306.
80		12.06		10.10	1.96	.163	78200	339.
81		12.06		9.71	2.35	.195	107050	323.
83	.155	7.90	.261	6.89	1.01	.147	2000	32.7
84		7.90		7.20	.70	.089	1000	34.0
85		7.90		7.07	.83	.105	1500	36.3
86		7.90		6.80	1.10	.139	4000	55.1
87		7.93		6.42	1.51	.190	10000	73.1
88		7.92		6.59	1.33	.168	7000	66.0
89	.195	11.97		10.89	1.08	.090	4000	57.2
90		11.96		11.19	.77	.064	7000	197.
91		11.97		11.16	.81	.068	10000	254.
92		11.97		10.90	1.07	.089	20000	291.
93		11.97		10.61	1.36	.114	30000	270.
94		11.98		10.39	1.59	.133	58860	388.
95		11.97		10.09	1.88	.157	87720	413.
96		11.97		9.97	2.00	.167	111060	463.

Table E.2. Volume Series Cont'd...............

Test	Q cfs	d cm	$\frac{u}{\sqrt{g d \Delta}}$	R cm	t cm	t/d	V cc	$\frac{V}{bt^2}$
97	.262	12.10	.276	11.49	.61	.050	2000	89.6
98		12.10		11.05	1.05	.087	6000	90.7
99		12.11		10.78	1.33	.110	10000	94.2
100		12.12		10.59	1.53	.126	16000	113.9
101		12.13		10.26	1.87	.154	26000	124.
102		12.13		9.93	2.20	.184	35500	122.
103	.233	12.03	.270	11.37	.66	.055	2000	76.5
104		12.03		11.59	.49	.041	1000	69.4
105		12.03		11.18	.85	.071	4000	97.3
106		12.03		10.81	1.22	.101	7500	84.
107		12.03		10.65	1.38	.115	11000	96.3
108		12.03	.270	10.40	1.63	.135	15000	94.
109		12.03		10.18	1.85	.154	20000	97.4
110		12.03		10.01	2.02	.168	25000	102.
111		12.04		9.89	2.15	.179	27000	97.3
112	.301	12.04	.269	11.19	.85	.071	2000	46.1
113		12.04		10.56	1.48	.123	10000	76.1
114		12.05		10.27	1.78	.148	20000	105.2
115		12.07		10.15	1.92	.159	30000	136.
116		12.08		9.80	2.28	.189	45400	146.
117		12.08		9.63	2.45	.203	55400	154.
118	.216	11.92	.271	11.34	.58	.049	1000	49.5
119		11.92		10.92	1.00	.084	4000	66.7
120		11.92		10.74	1.18	.099	7000	83.8
121		11.93		10.52	1.41	.118	11000	92.2
122		11.93		10.20	1.73	.145	16000	89.1
123		11.93		9.86	2.07	.174	23000	89.5

Table E.3. Angled Barrier Tests

Test	Barrier Clearance cm	d cm	t/d	Q cts	Θ degrees
1	3	5.97	.497	.258	56
2	3	5.97	.497	.258	54
3	3	5.71	.475	.320	40
4	3	6.32	.525	.349	45
5	5.5	9.54	.424	.411	57
6	5.5	9.08	.394	.509	50
7	5.5	9.08	.394	.639	45
8	5.5	9.16	.400	.748	37
9	5.5	9.61	.427	.976	37
10	18	20.06	.100	1.20	37
11	18	20.00	.100	1.25	40
12	18	20.02	.101	1.46	32
13	18	19.95	.098	1.57	30
14	18	19.95	.098	1.92	27
15	18	19.9	.096	2.23	25
16	18	19.98	.099	2.47	20
17	18	20.02	.101	1.77	27
18	18	19.98	.099	.897	45
19	18	19.97	.099	.96	45
20	18	19.96	.098	1.08	40
21	18	19.98	.099	.818	45
22	18	20.02	.101	.576	90
23	18	20.02	.101	.686	55
24	14	20.00	.300	.774	90
25	14	19.98	.299	.941	55
26	14	20.01	.300	1.00	50
27	14	20.00	.300	1.23	45
28	14	20.02	.301	1.37	40
29	14	20.00	.300	1.62	35
30	14	20.00	.300	1.78	30
31	14	19.94	.298	2.02	30
32	14	19.99	.300	2.18	27
33	14	20.02	.300	2.41	27
34	7	10.00	.300	.552	40
35	7	10.02	.301	.312	90
36	7	9.98	.299	.385	57
37	7	10.02	.301	.741	30
38	7	10.00	.300	.850	25
39	7	9.98	.299	1.05	25
40	7	10.00	.300	1.25	22
41	7	10.04	.303	.371	55
42	7	8.00	.125	.366	27
43	7	8.01	.126	.272	42
44	7	8.00	.125	.328	32
45	7	8.00	.125	.471	20

Table E.3. Angled Barrier Tests

Test	Barrier Clearance cm	d cm	t/d	Q cts	Θ degrees
46	7	8.02	.127	.433	22
47	7	7.99	.124	.617	18
48	7	8.01	.126	.150	90
49	7	8.00	.125	.181	90
50	4.8	8.00	.400	.181	90
51	4.8	8.00	.400	.235	90
52	4.8	7.98	.398	.298	55
53	4.8	8.02	.401	.379	45
541	4.8	7.98	.398	.491	30
55	4.8	7.98	.398	.570	28
56	4.8	8.00	.400	.749	25
57	9	10.03	.103	.360	42
58	9	10.00	.100	.553	25
59	9	10.01	.101	.504	28
60	9	10.00	.100	.469	30
61	9	10.04	.104	.418	37
6	9	10.00	.100	.490	20
67	9	10.00	.100	.403	25
68	9	9.98	.098	.326	35
69	9	10.00	.100	.283	40
70	9	9.98	.098	.239	52
71	9	9.98	.09	.341	32
72	9	9.98	.098	.394	27
73	9	10.00	.100	.551	23
74	9	10.02	.102	.617	20
75	9	10.00	.100	.775	15
76	9	10.00	.100	.931	13