



THE COLLEGE OF AERONAUTICS
CRANFIELD

VOLUME 2

THESIS

TITLE: DISCHARGE COEFFICIENT AND
JET DEFLECTION STUDIES FOR
COMBUSTOR LINER
AIR ENTRY HOLES

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DATE JUNE 1964

FIGURES

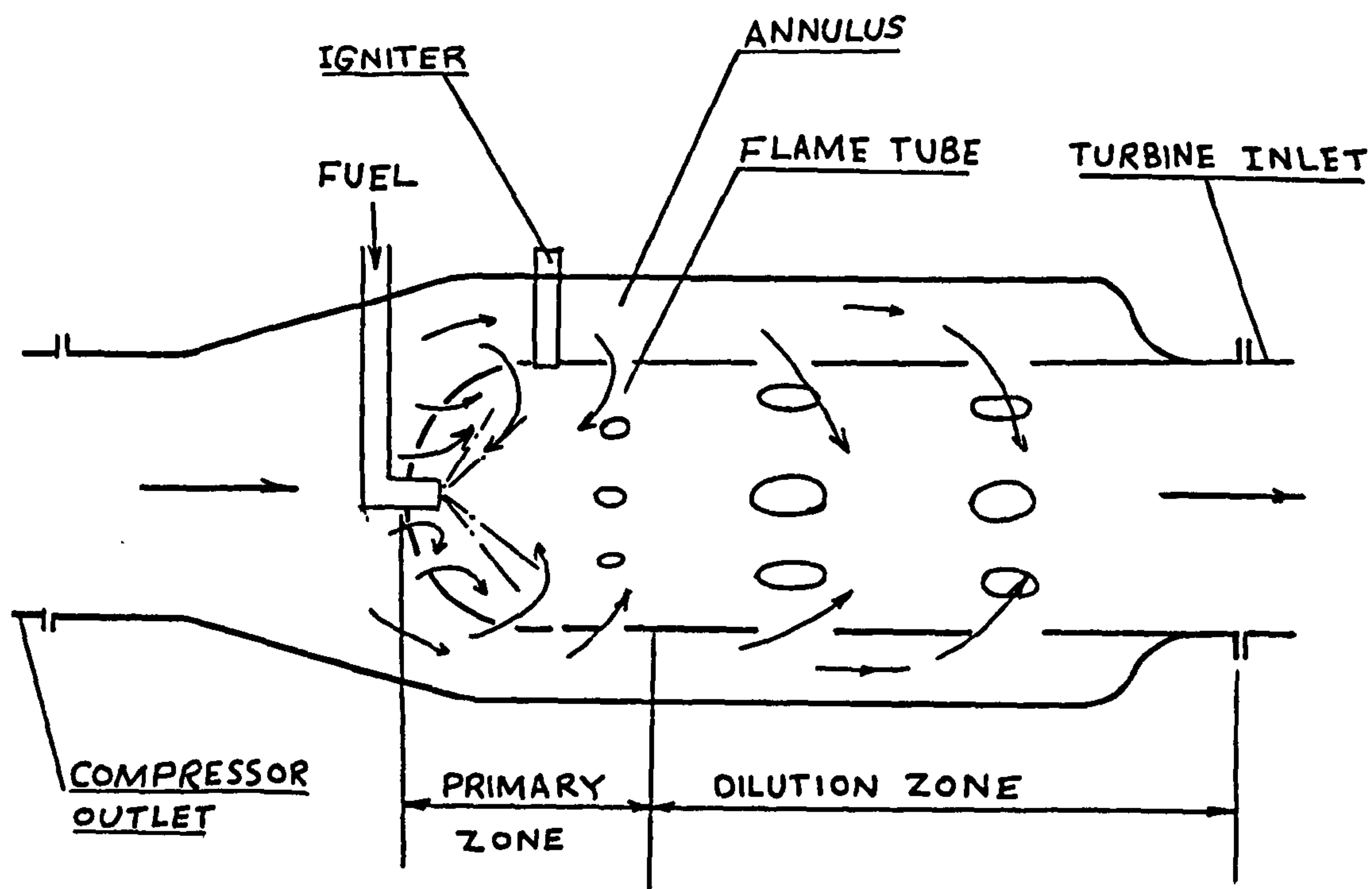
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Variable print quality

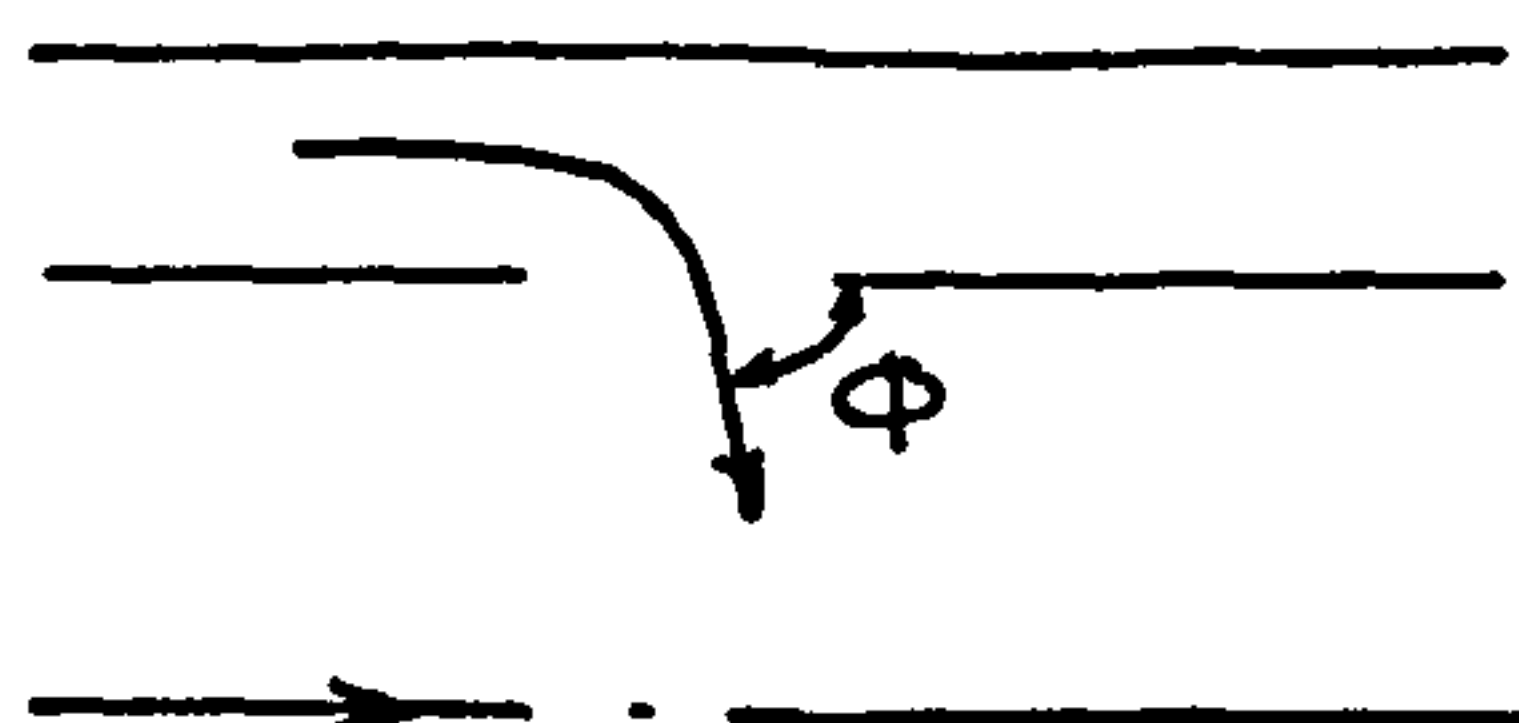
C O N T E N T S

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FIGURES	126
APPENDICES FIGURES.	26
PHOTOGRAPHIC PLATES	24

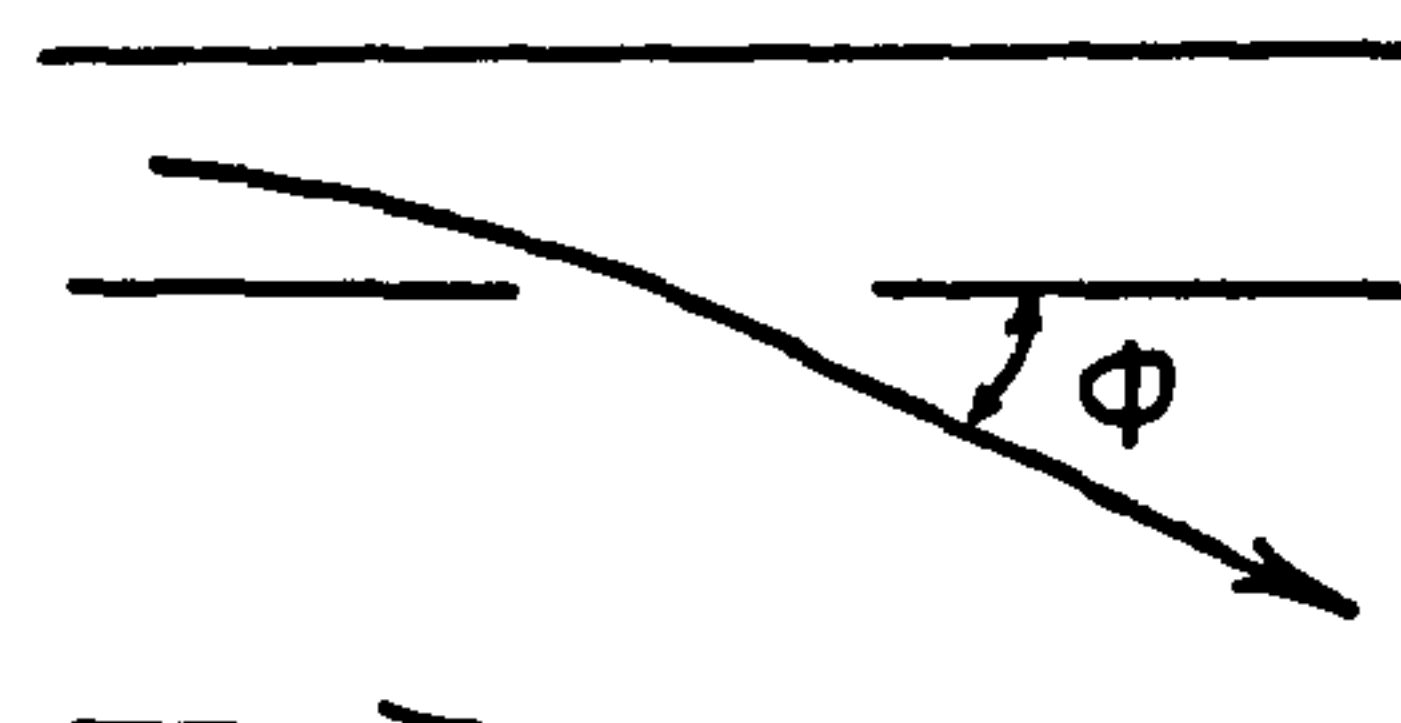


Typical Tubular Combustor

Typical Liner Hole at different flow conditions

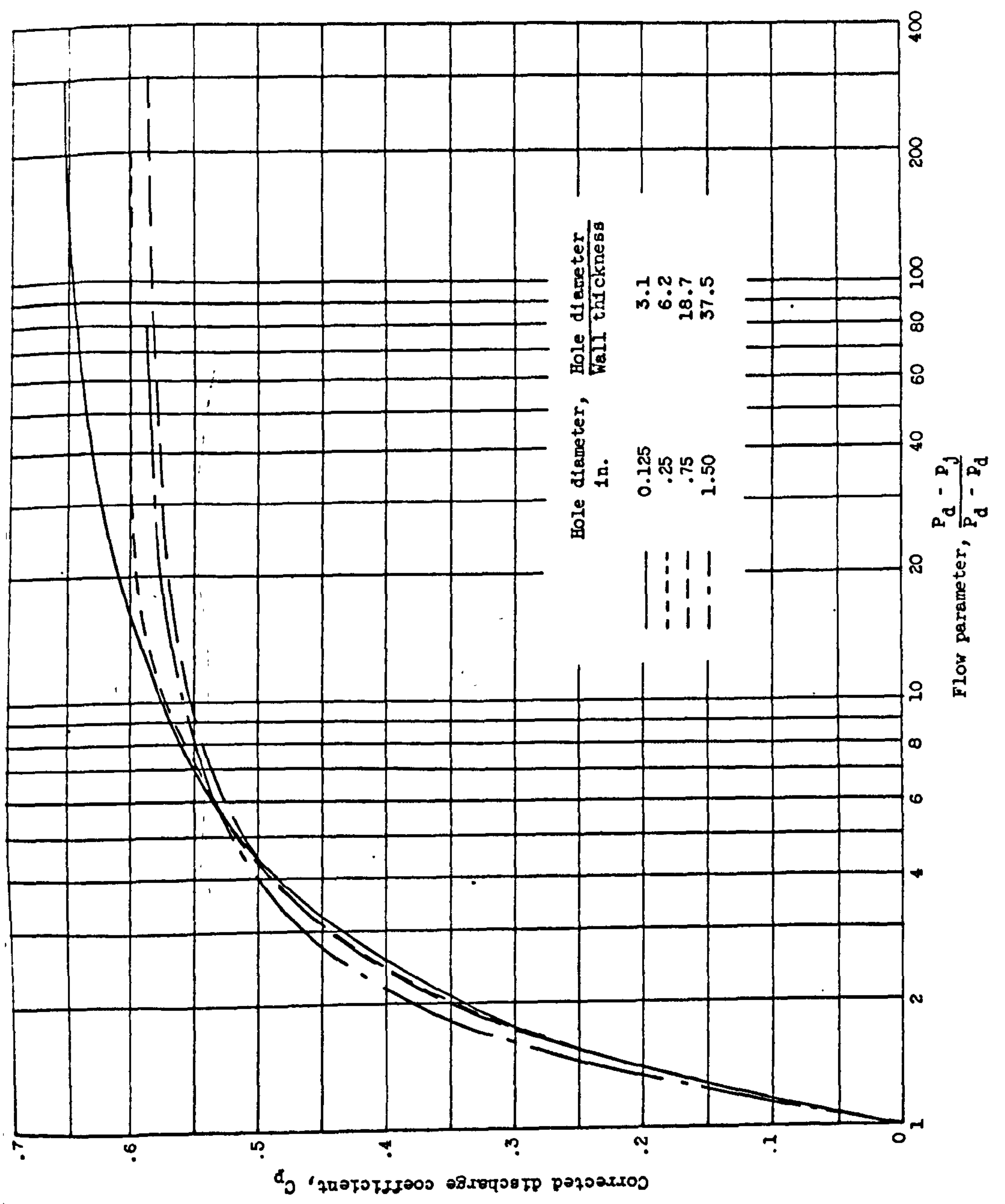


Adequate Penetration
Short Flame tube (ϕ large)
High Pressure loss factor
High Flow parameter

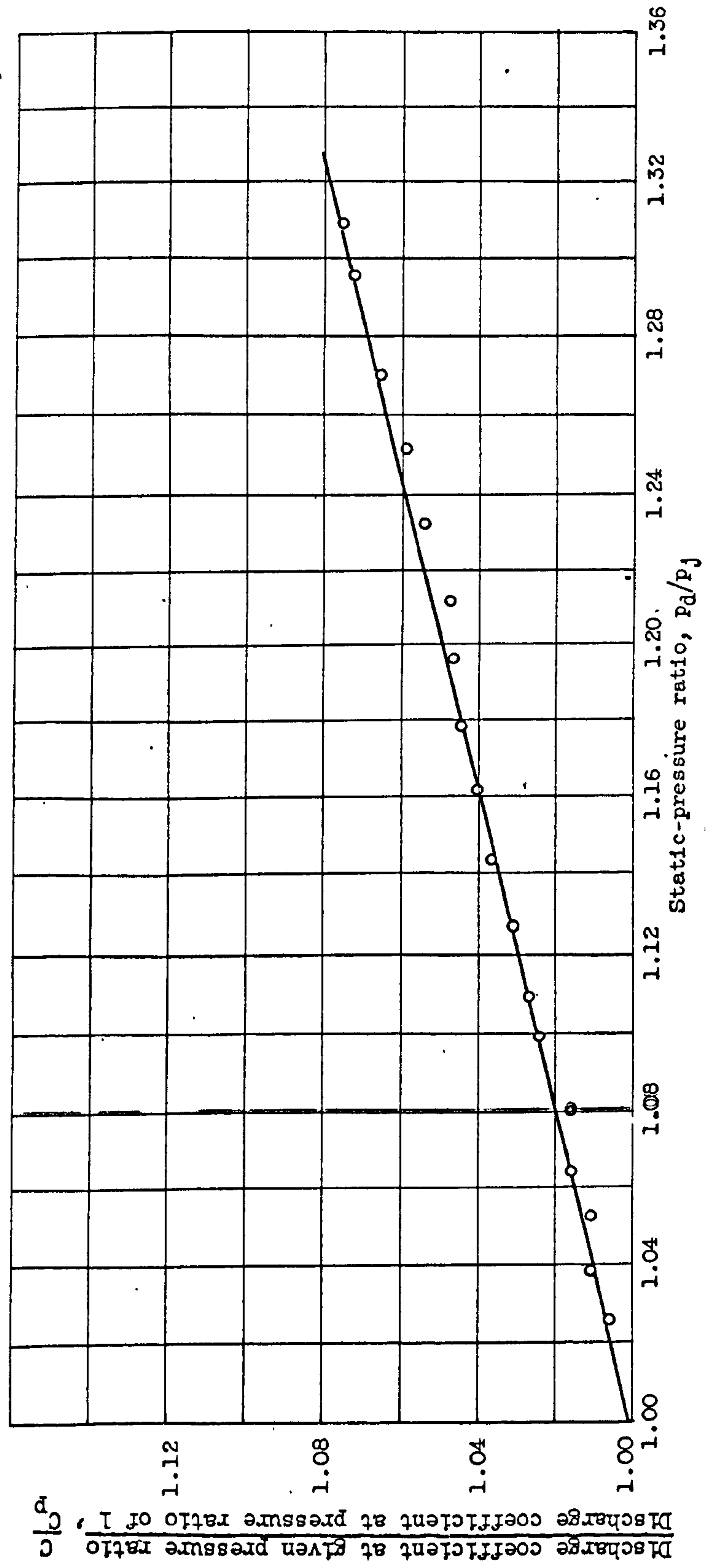


Weak Penetration
Long Flame tube (ϕ small)
Low Pressure loss factor
Low flow parameter

Effect of hole diameter on corrected discharge coefficient .
 Wall thickness at hole 0.04 inch . (5)

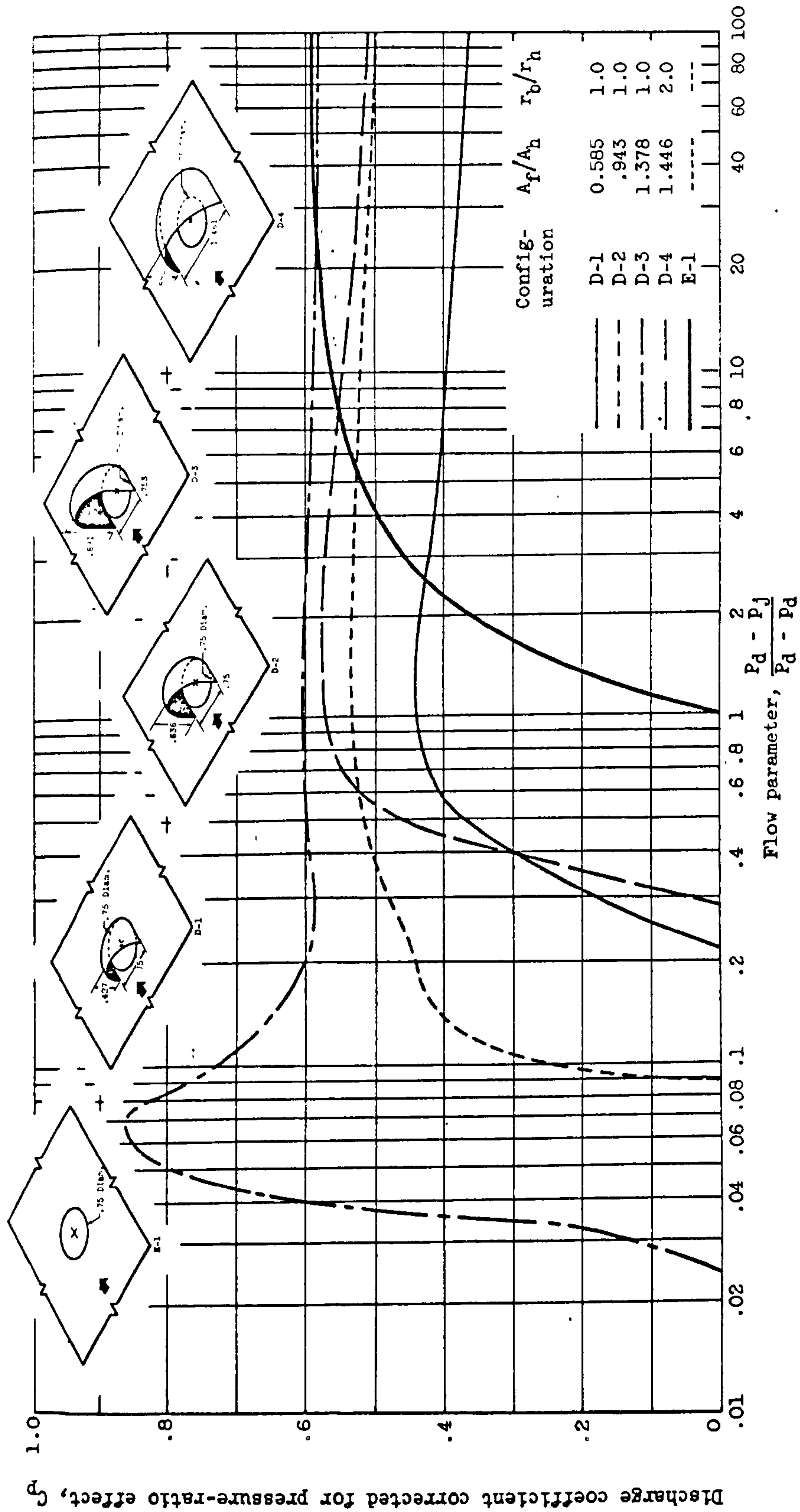


Pressure ratio correction for hole discharge coefficient . (5)

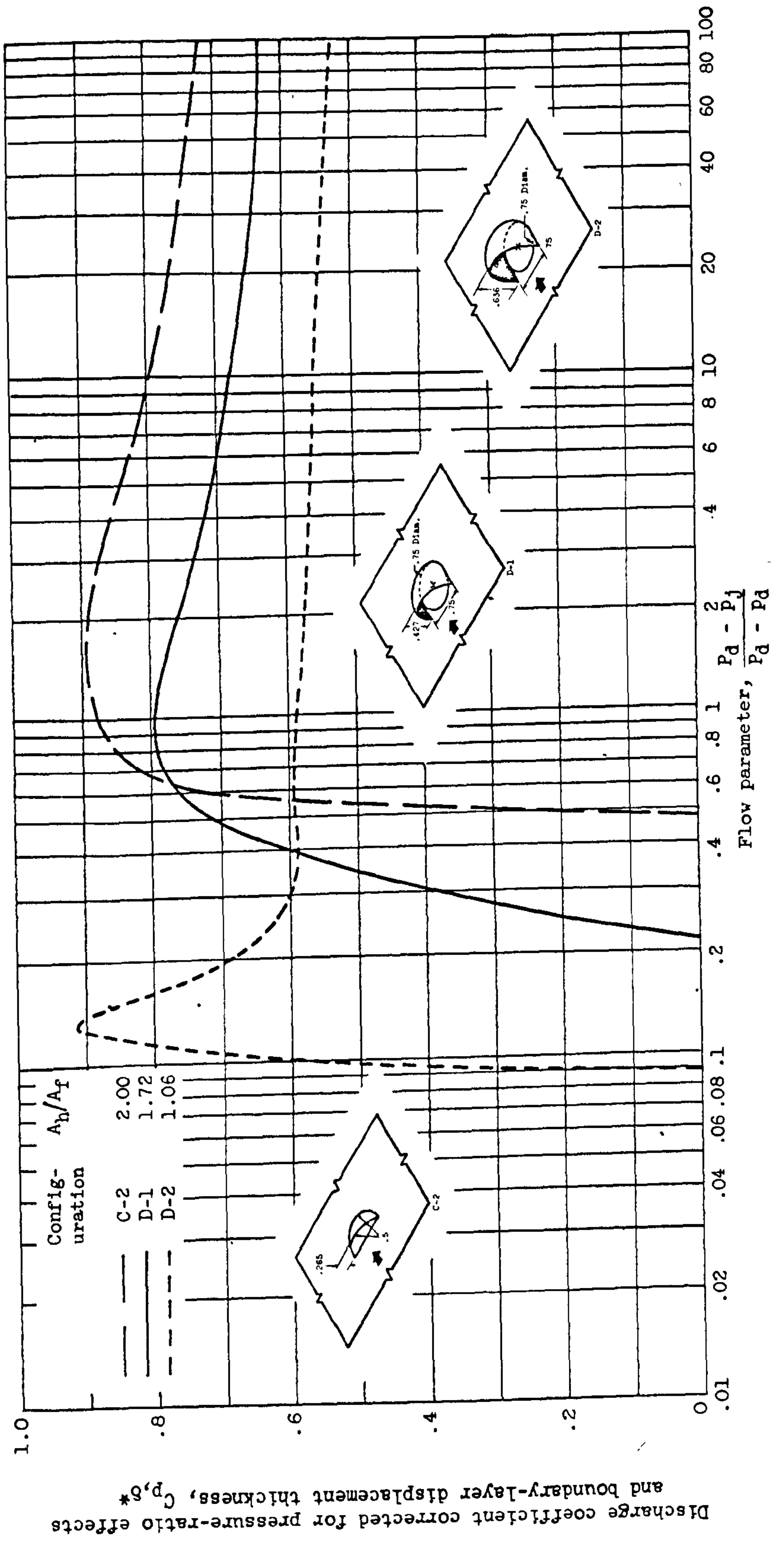


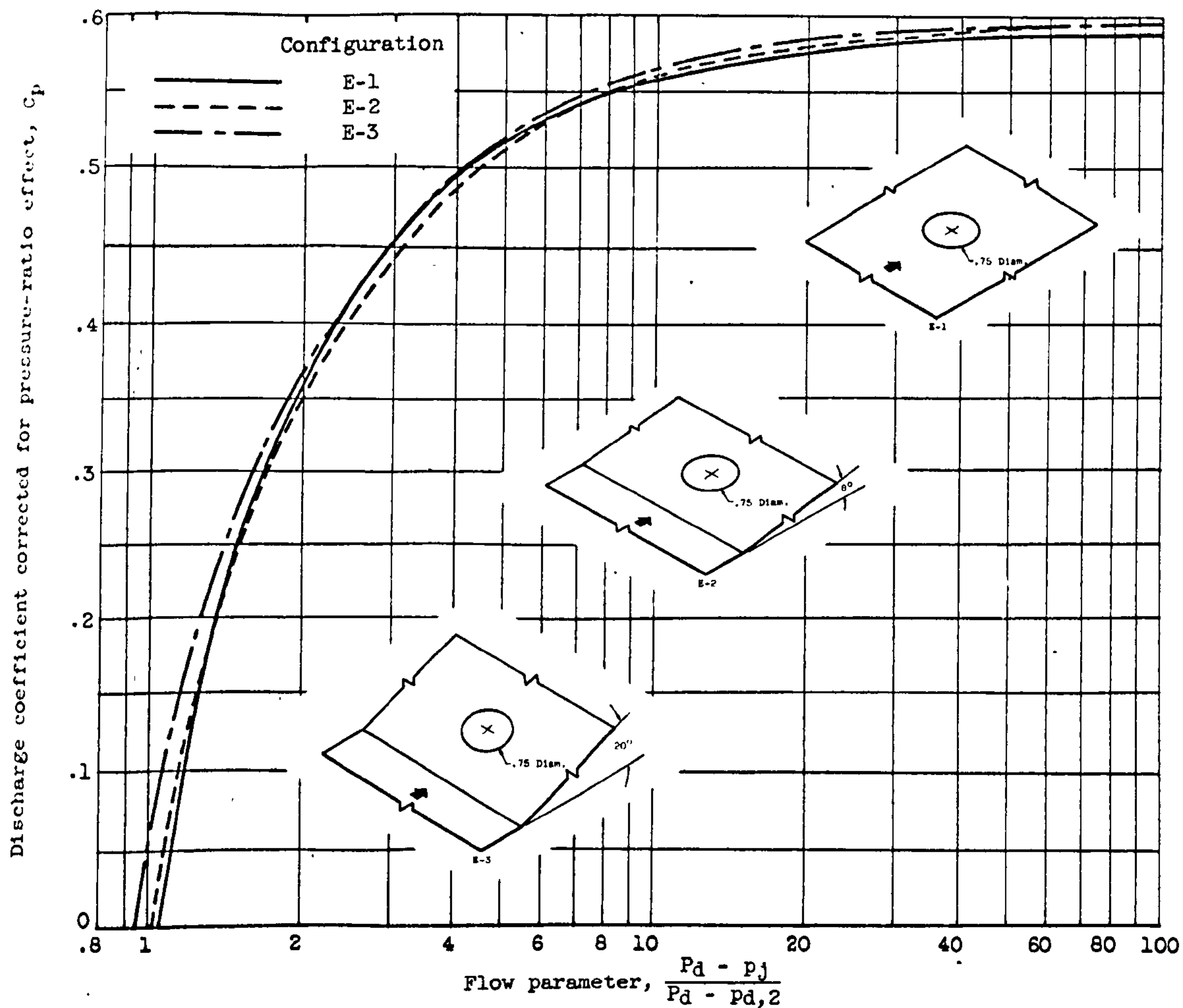
Effect of scoop, mounted on flush circular hole on discharge coefficient ,

(based on circular hole area) . [6]



Comparison of discharge coefficients for scoops -over-hole with thump nail-
Type scoop . (Discharge coefficient based on scoop face area) . [6]

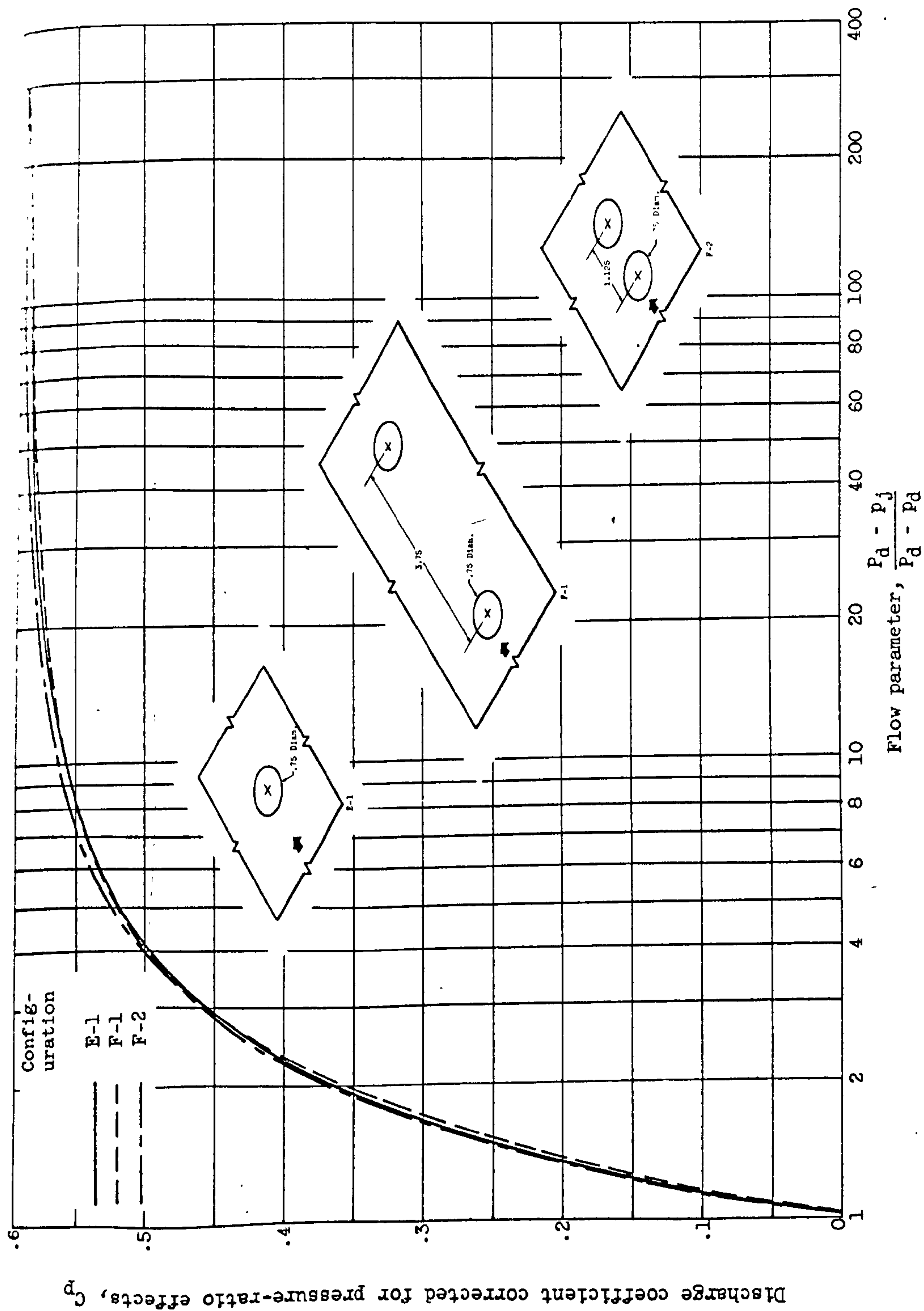




(a) Flush circular hole with 0.75-inch diameter.

EFFECT OF WALL INCLINATION ON HOLE CORRECTED
DISCHARGE COEFFICIENT. [6]

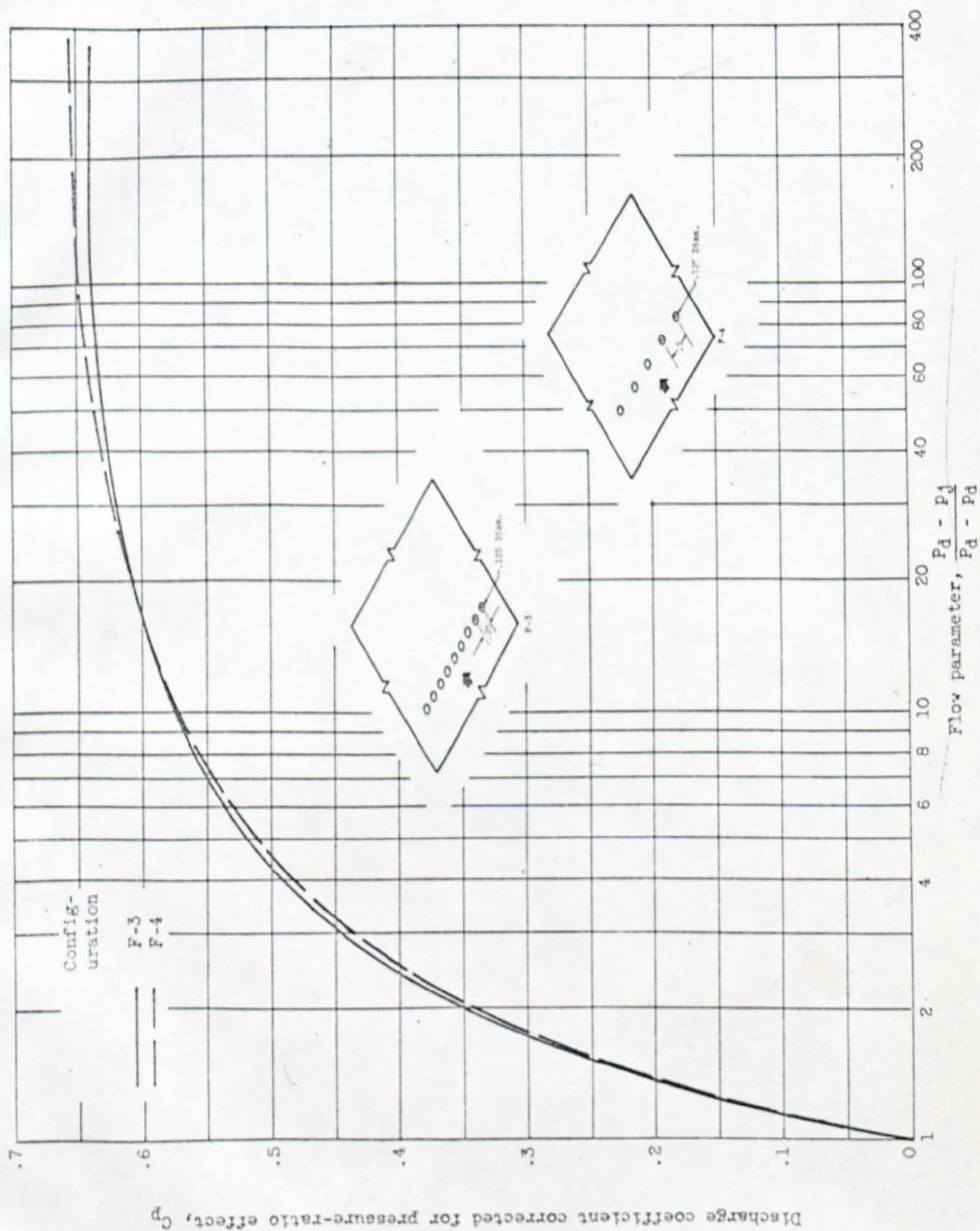
Effect of proximity of multiple holes on corrected discharge coefficient .(6)



(a) Holes in line. (Configuration E-1 included for comparison.)

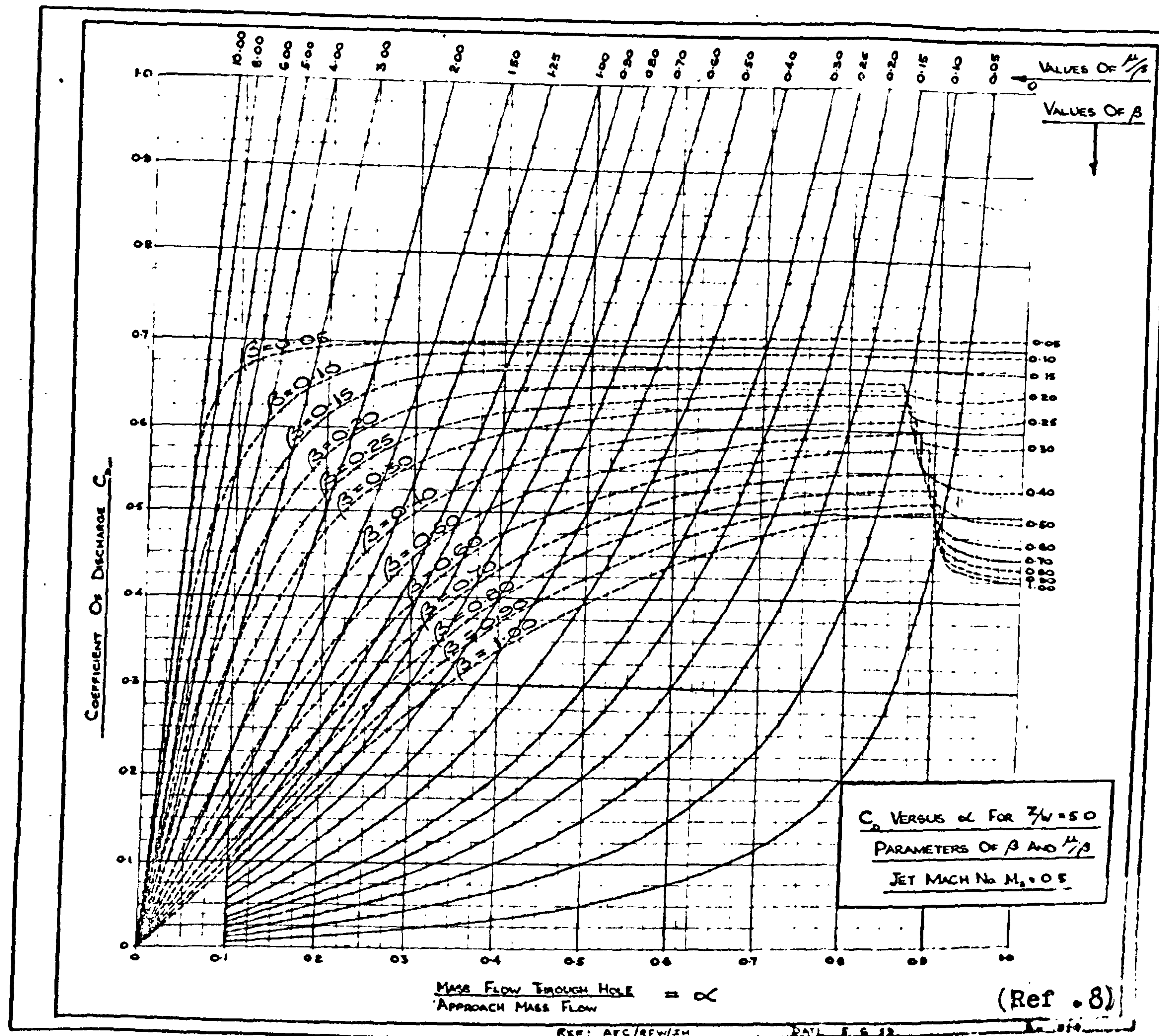
Effect of proximity of multiple holes on corrected discharge coefficient.

(Ref. 6) .

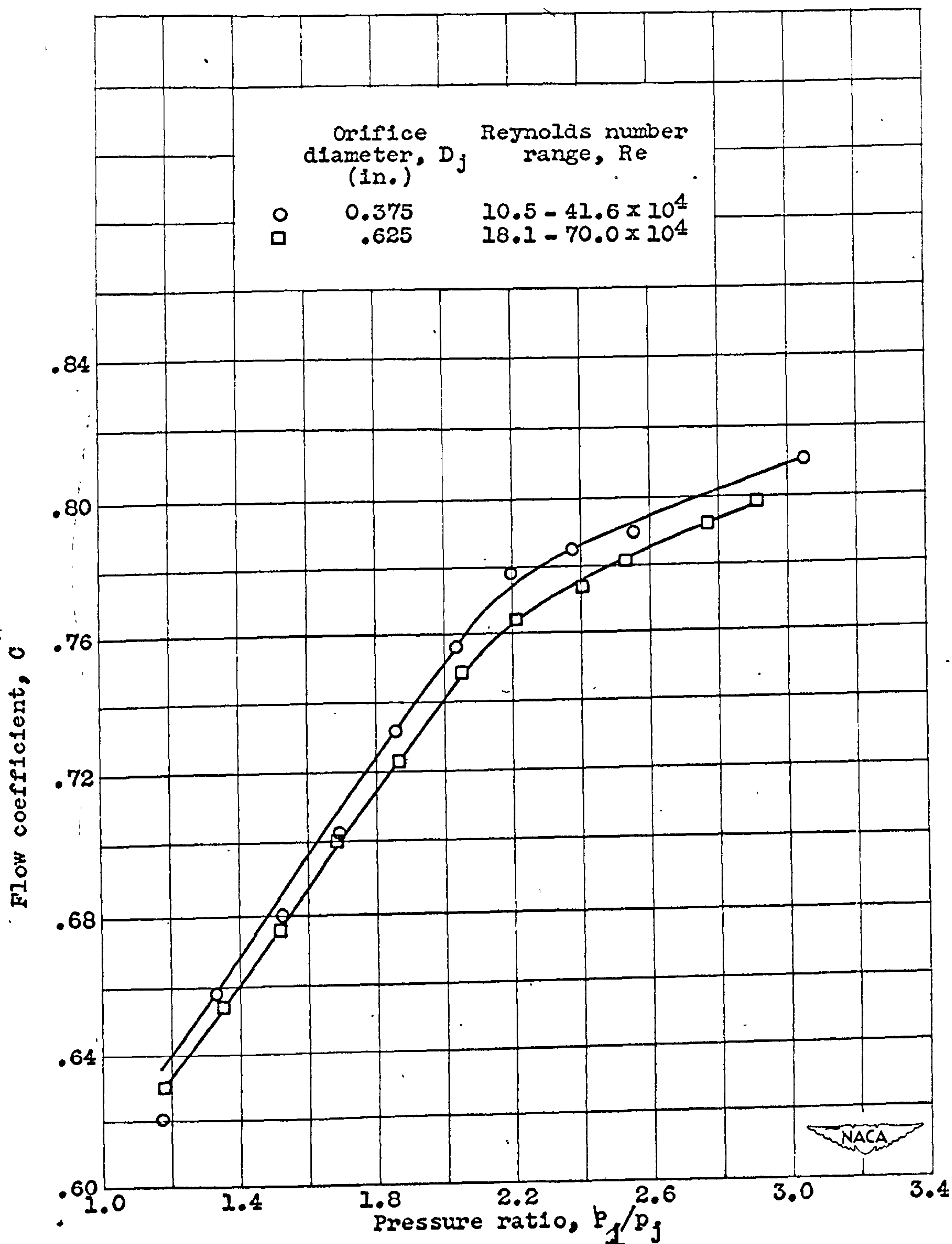


(b) Holes side by side.

FIG. 9



Z/W = Aspect ratio of
approach duct .
= Area ratio .



VARIATION OF DISCHARGE COEFFICIENT WITH PRESSURE RATIO FOR TWO CIRCULAR ORIFICES, JET TEMP. 70°F. [3]

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Poor text in the original
thesis.

Some text bound close to
the spine.

Some images distorted

FIG. 11

Variation of angle of jet deflection with bleed for various values of ratio of total orifice area to duct area.

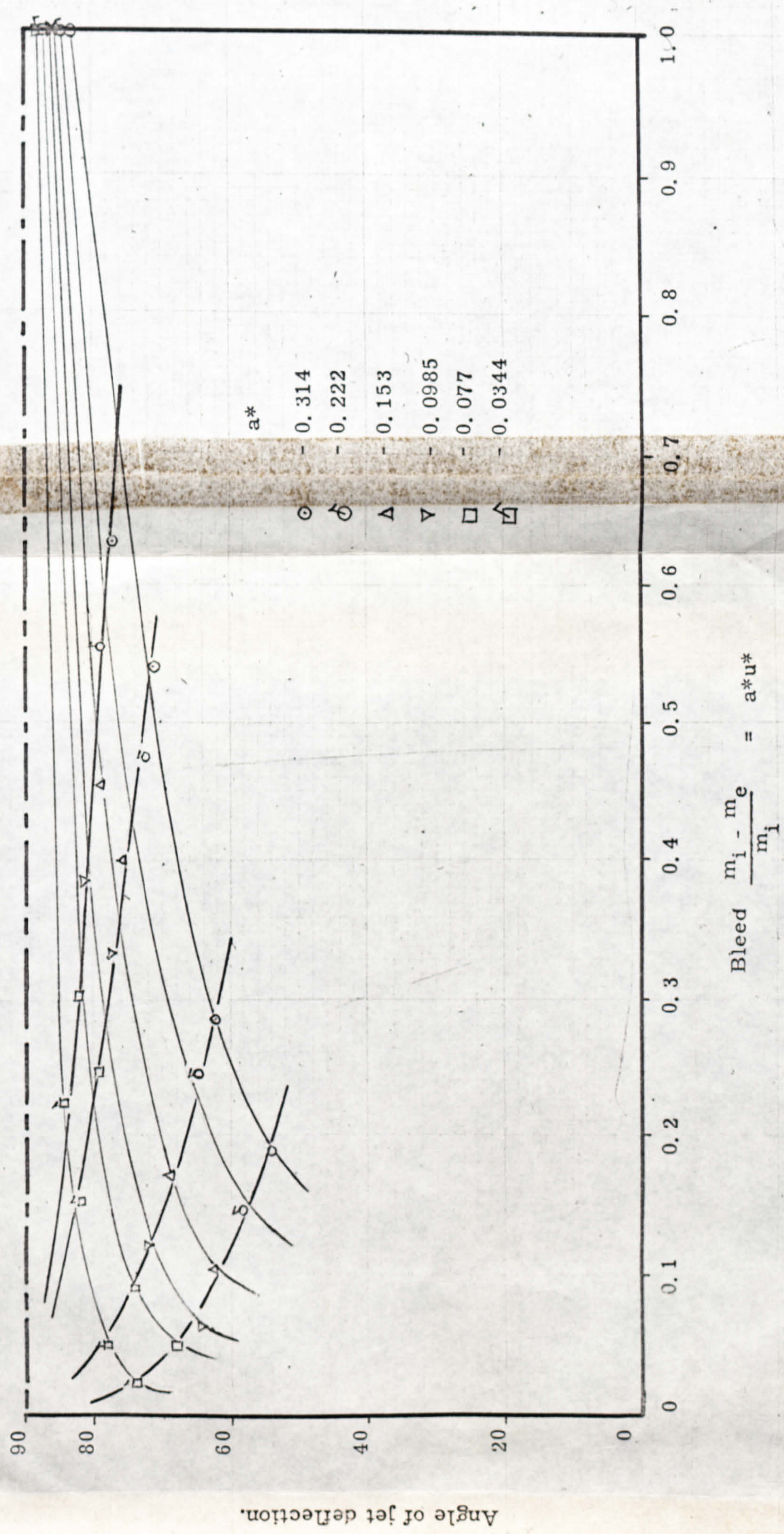
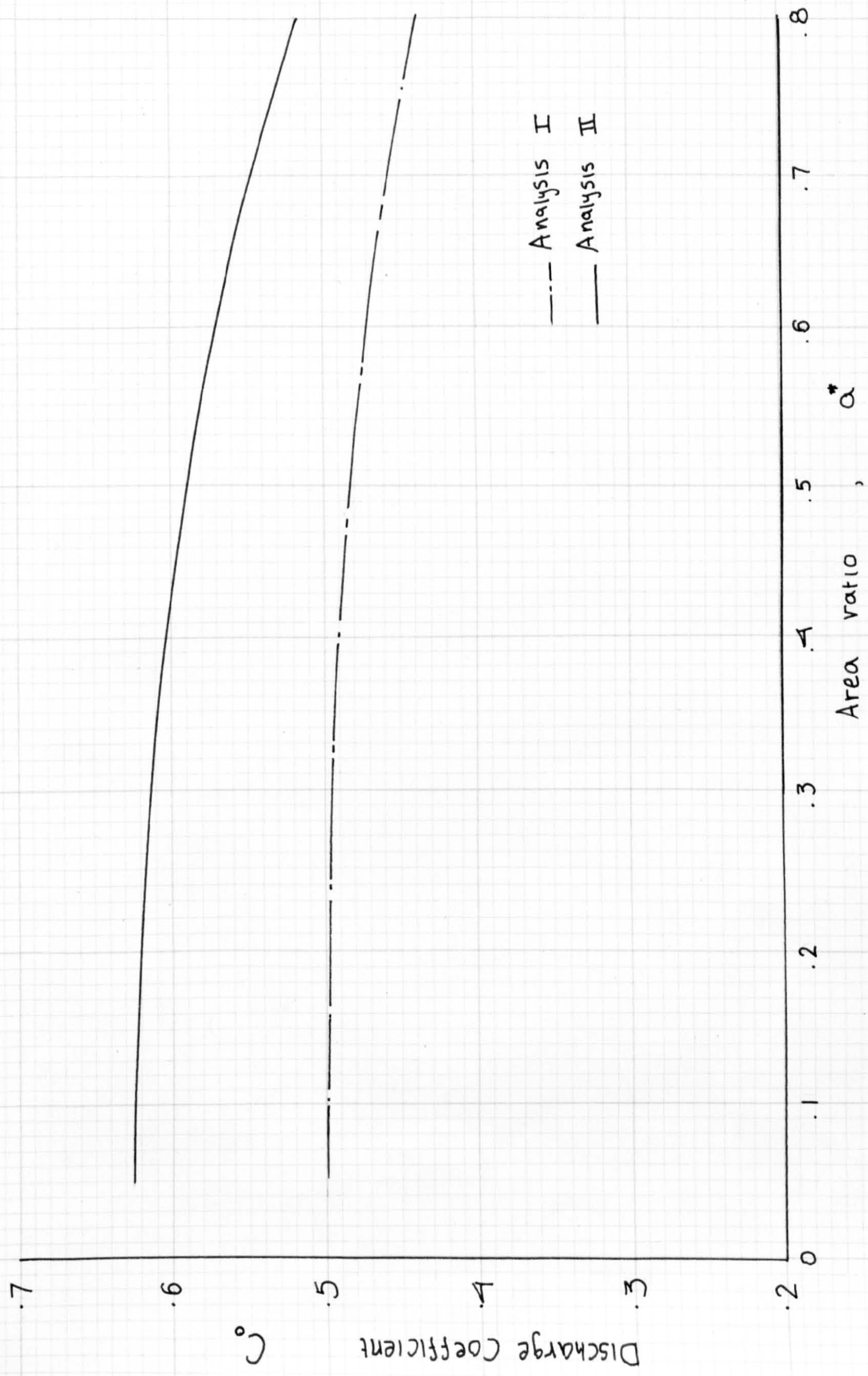


FIG. 12



Theoretical variation of Discharge coefficient with area ratio .
(No cross flow) .

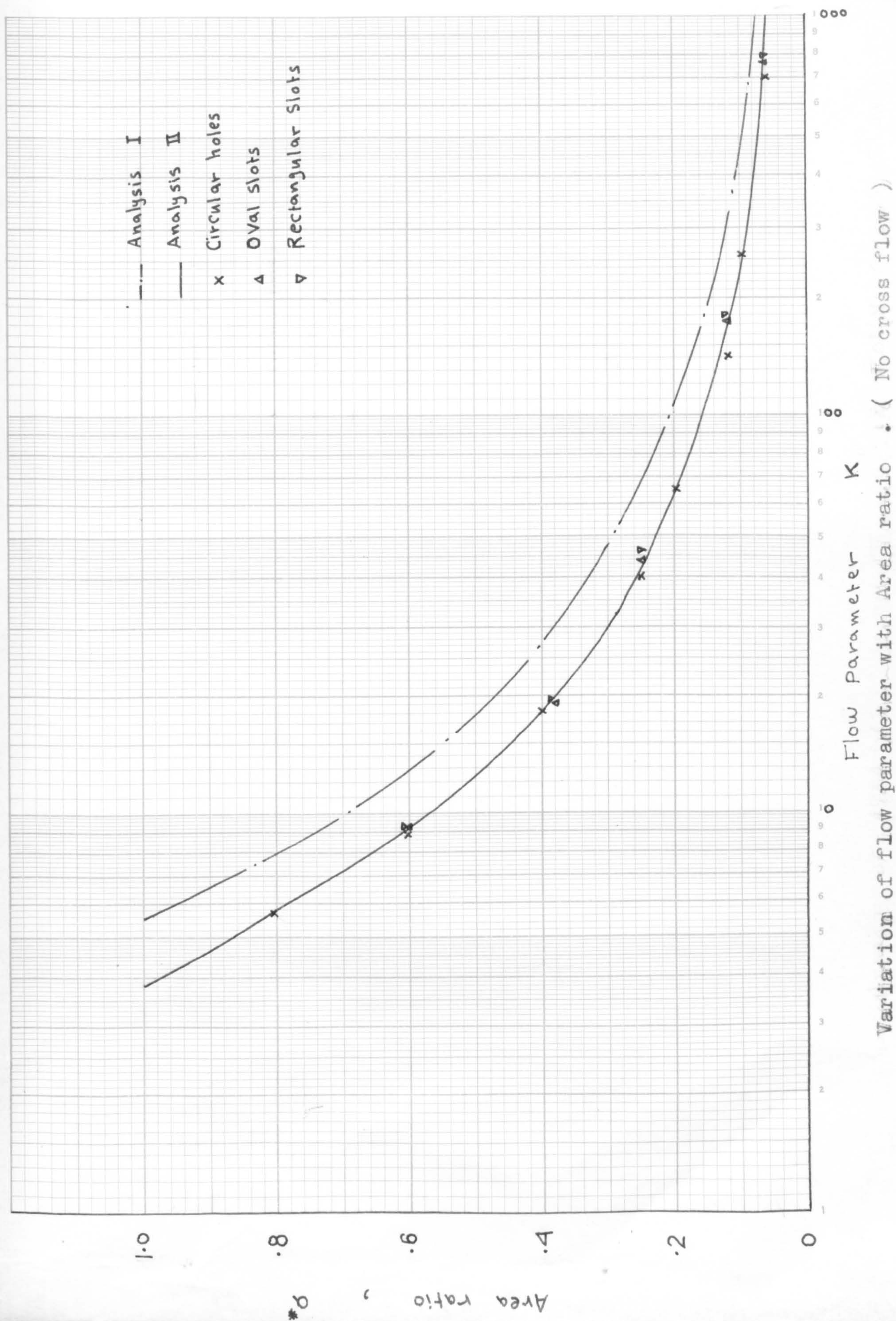
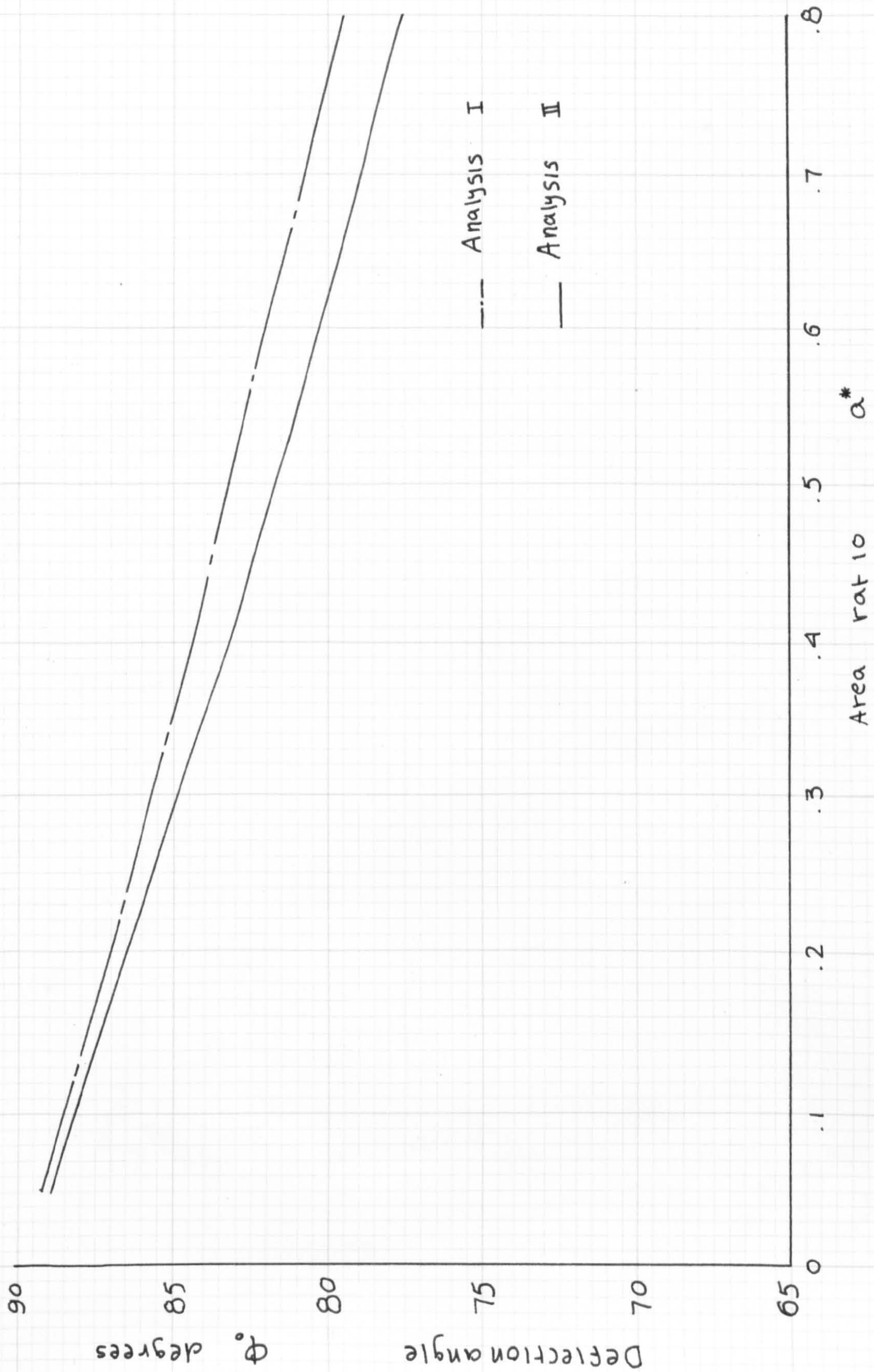
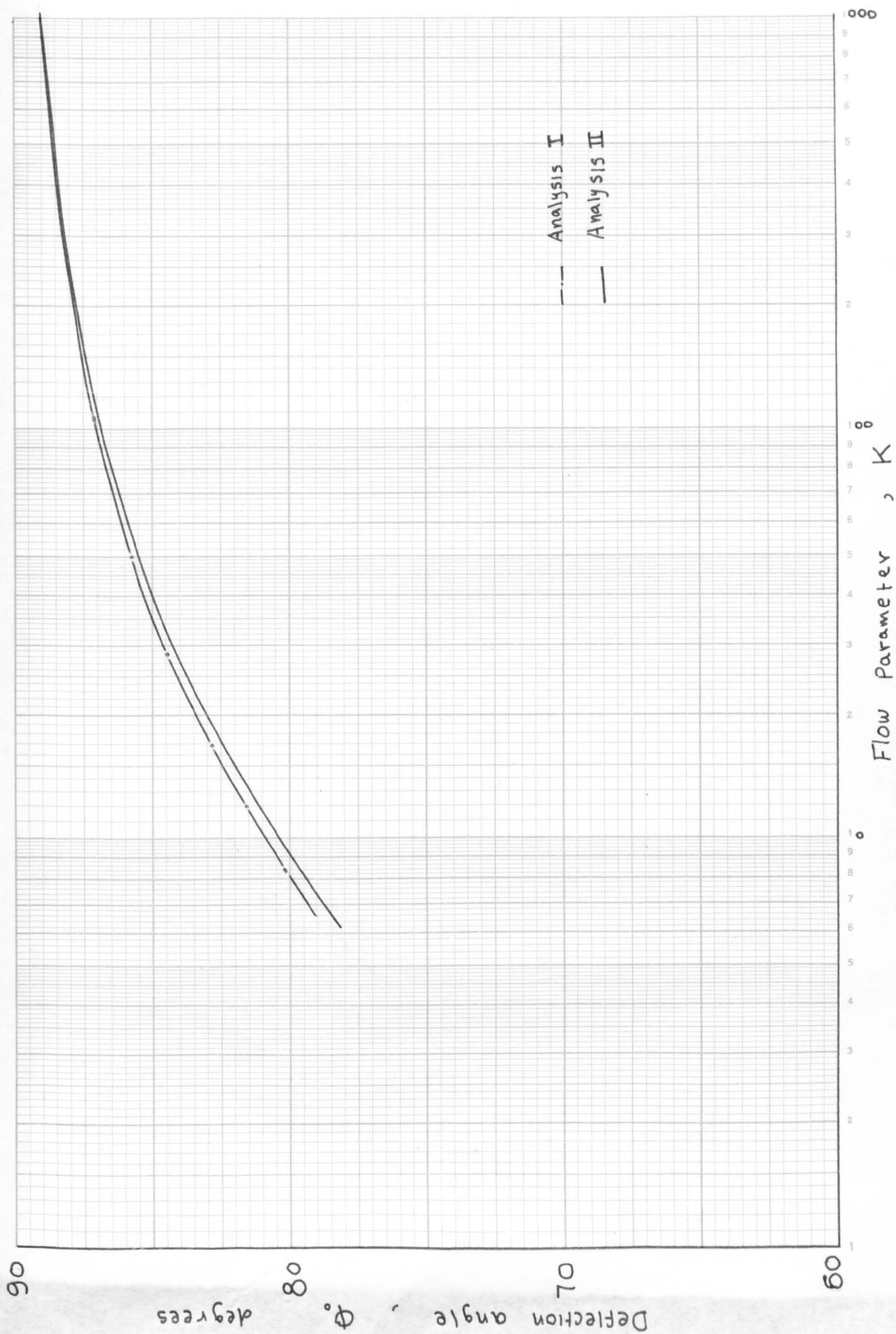


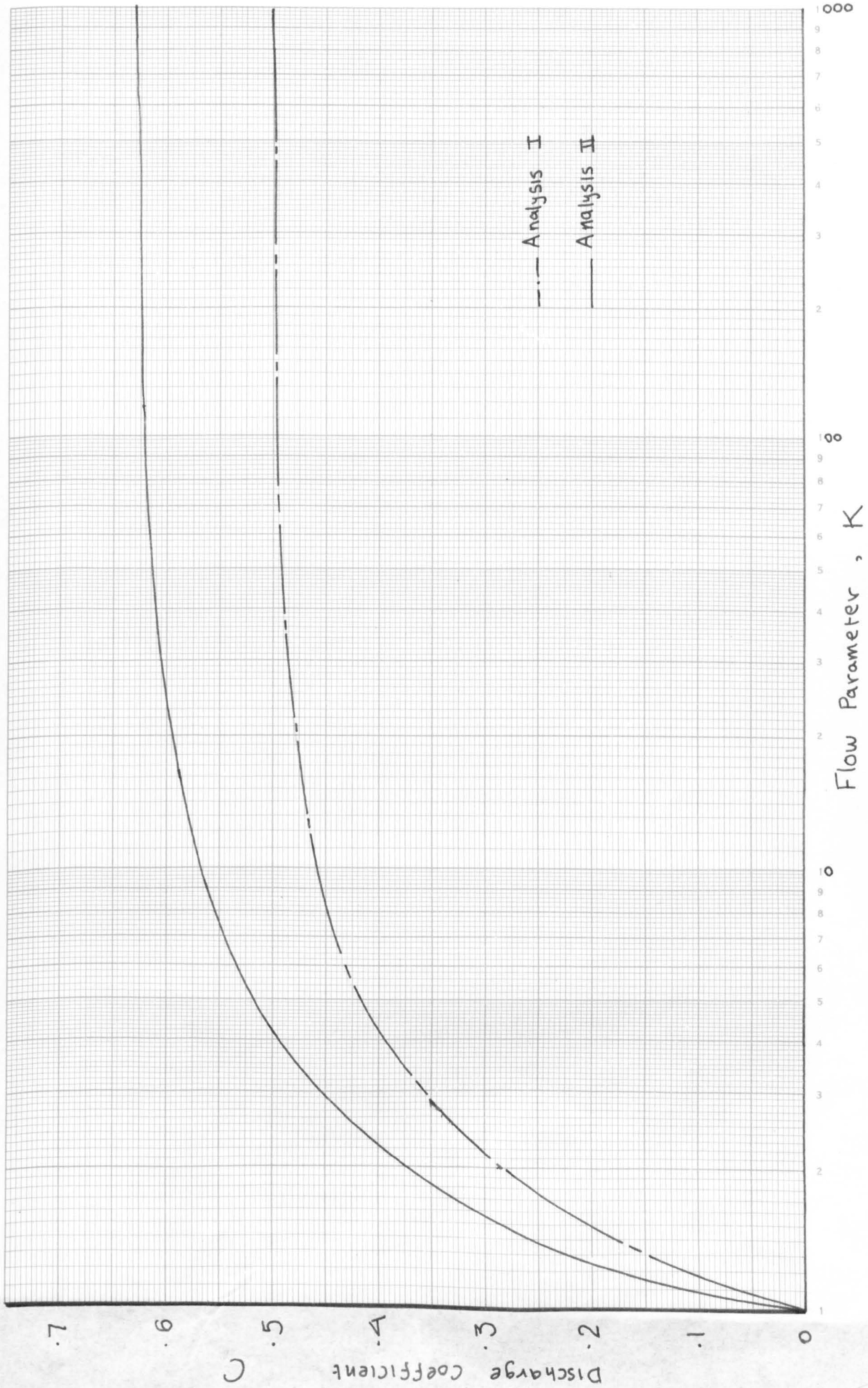
FIG. 14



Theoretical variation of Deflection angle with Area ratio. (No cross flow)

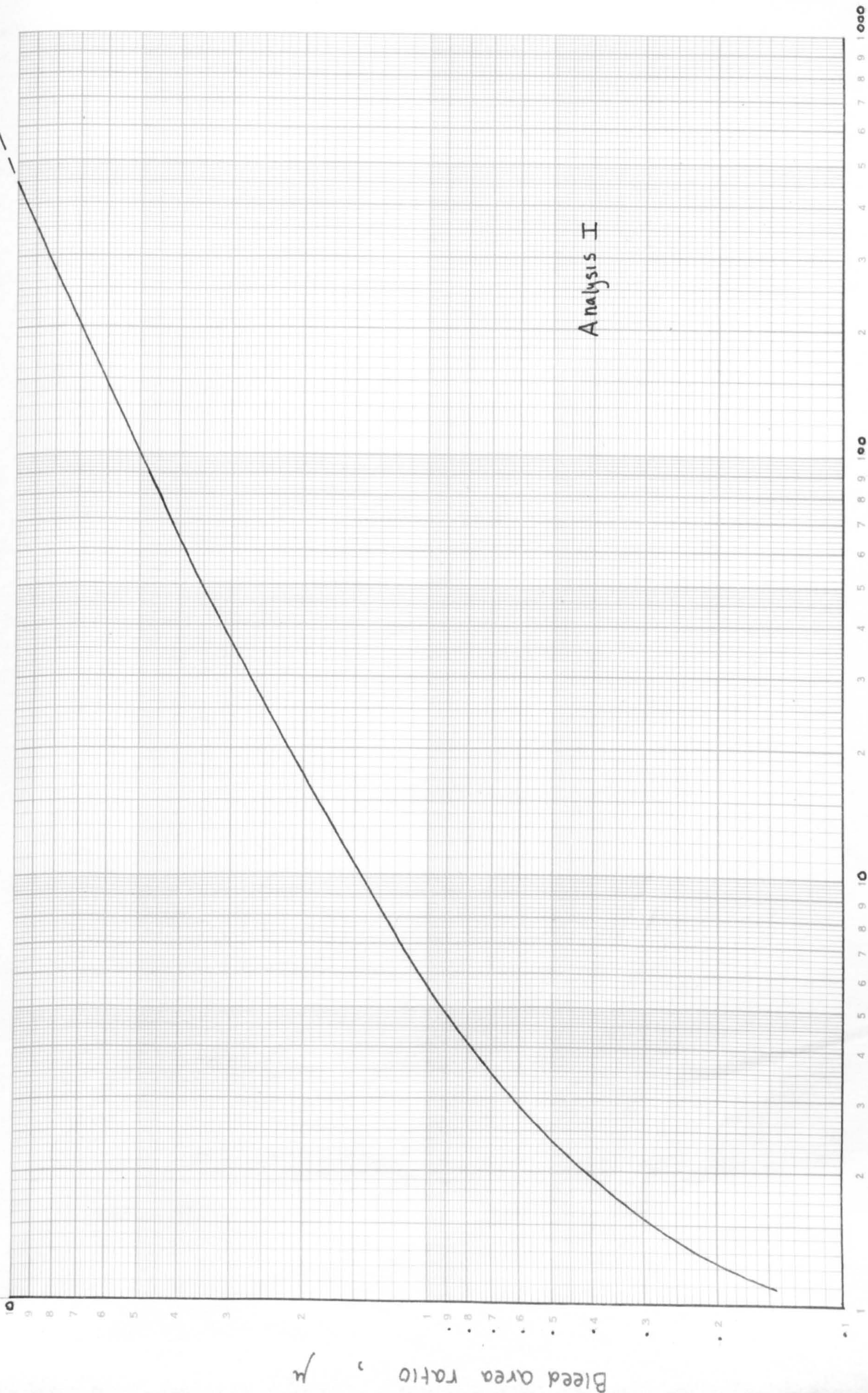


Theoretical variation of Deflection angle with flow parameter. (No cross flow)



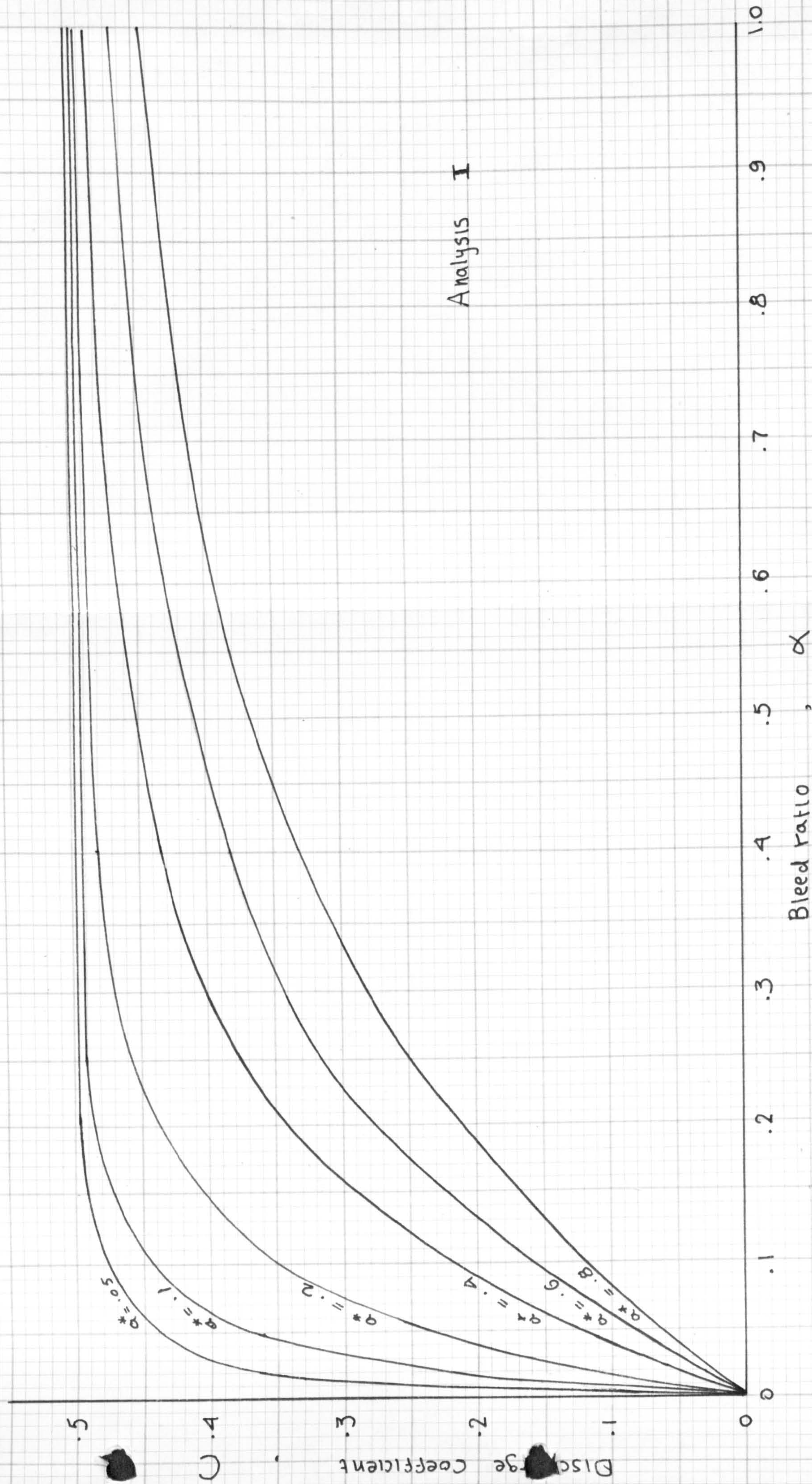
Theoretical variation of Discharge coefficient with flow parameter .

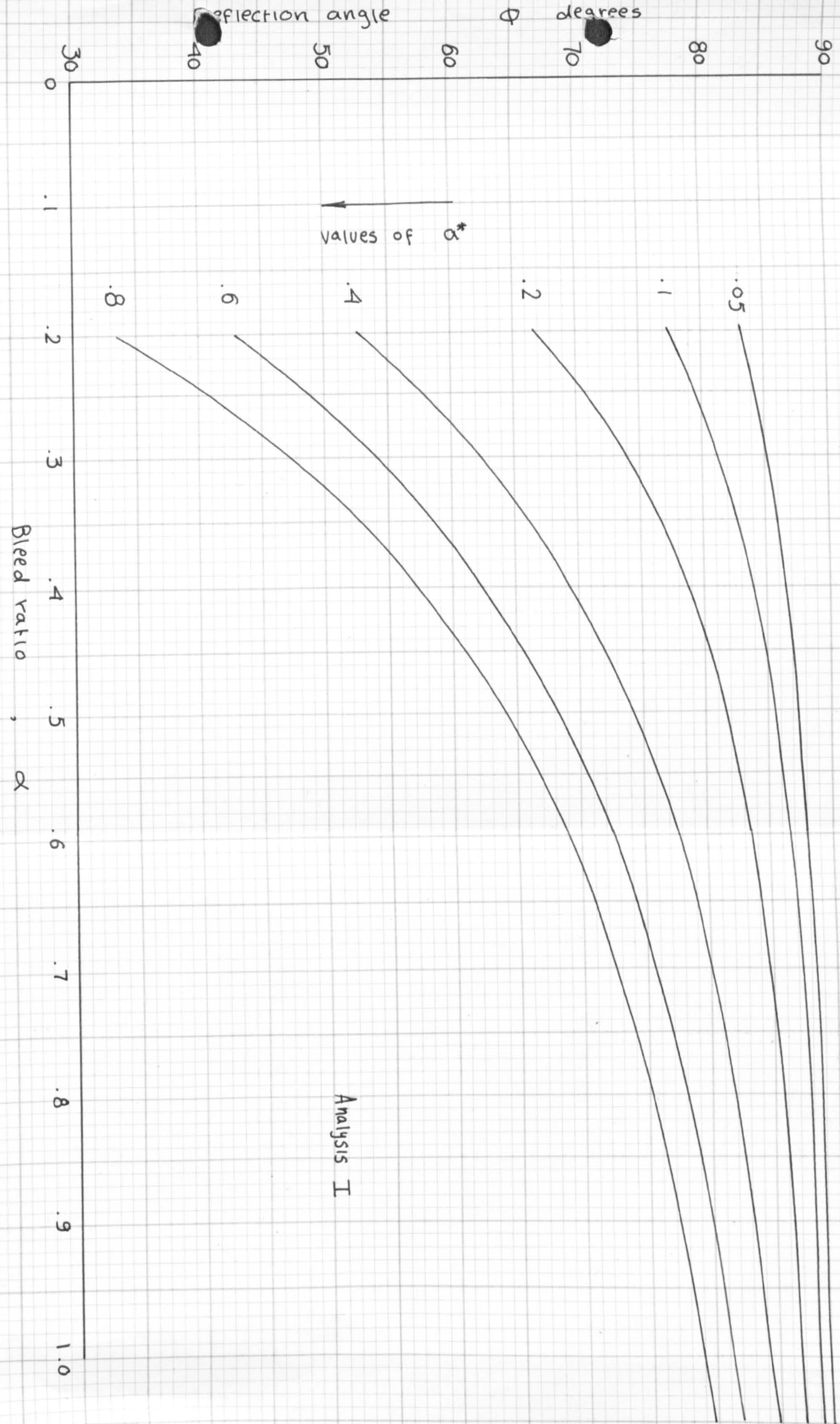
Analysis I



Theoretical variation of flow parameter with Bleed Area ratio •

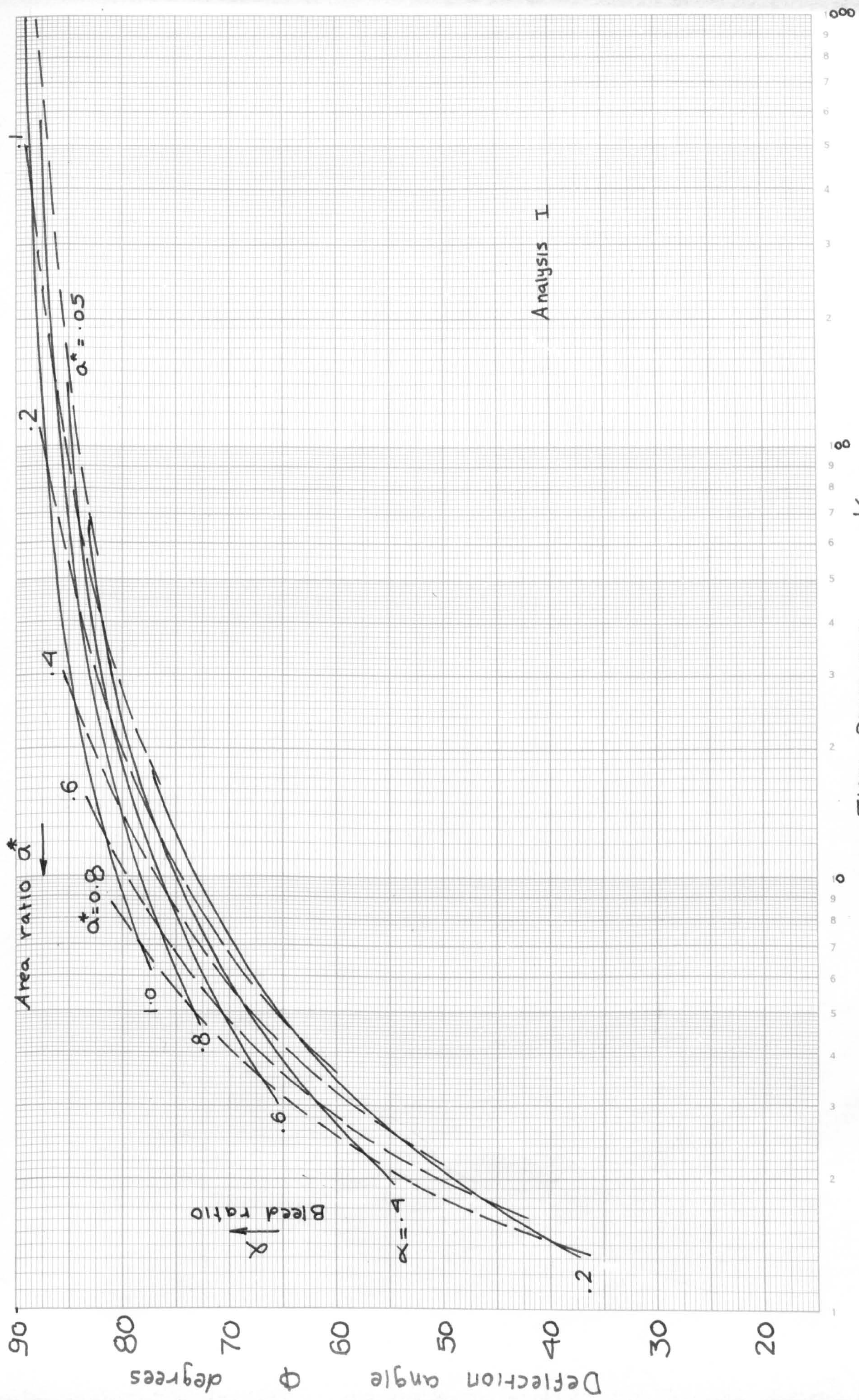
Theoretical variation of Discharge coefficient with Bleed and Area ratios





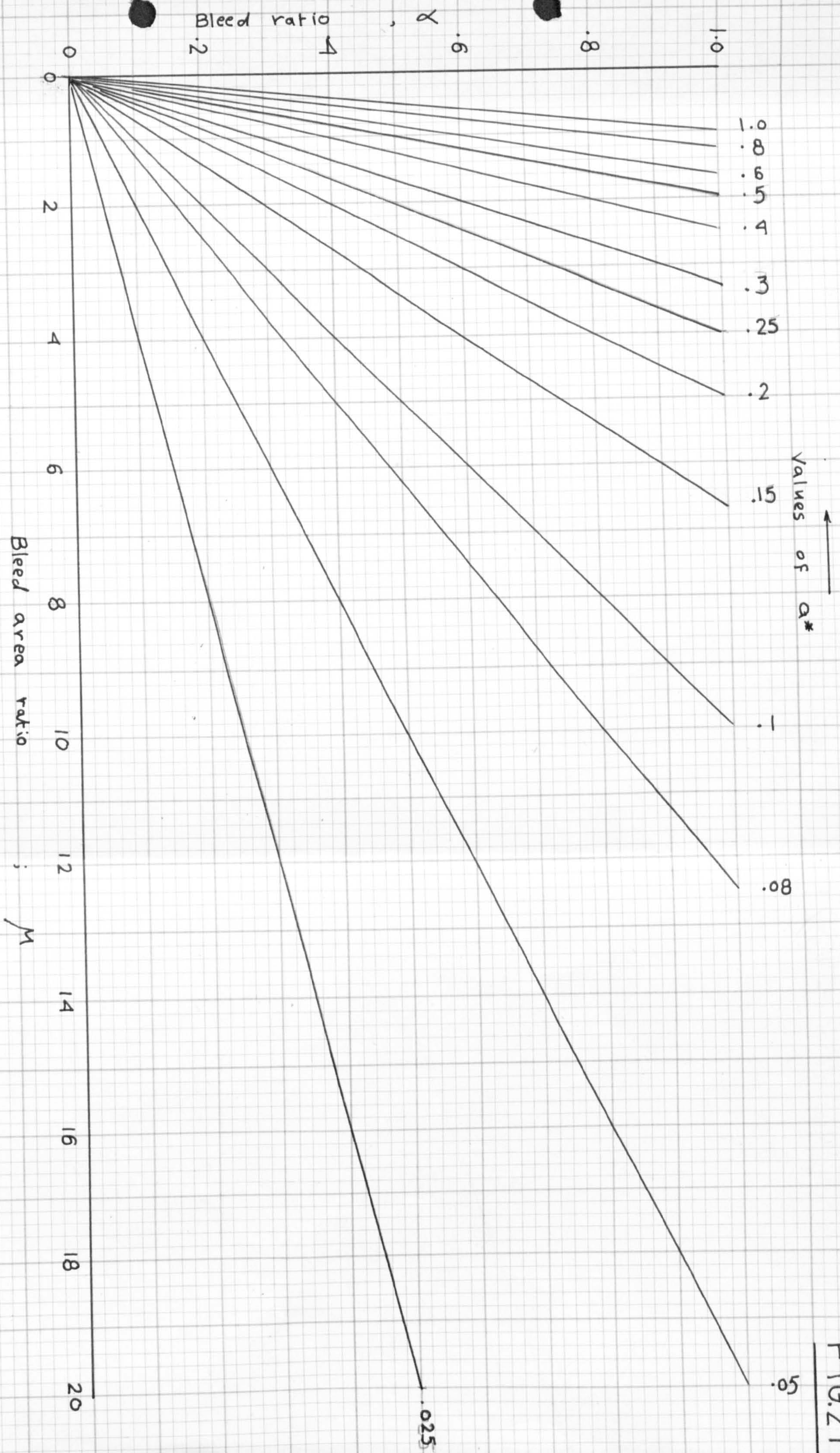
Analysis I

Theoretical variation of Deflection angle with Bleed and Area ratios.

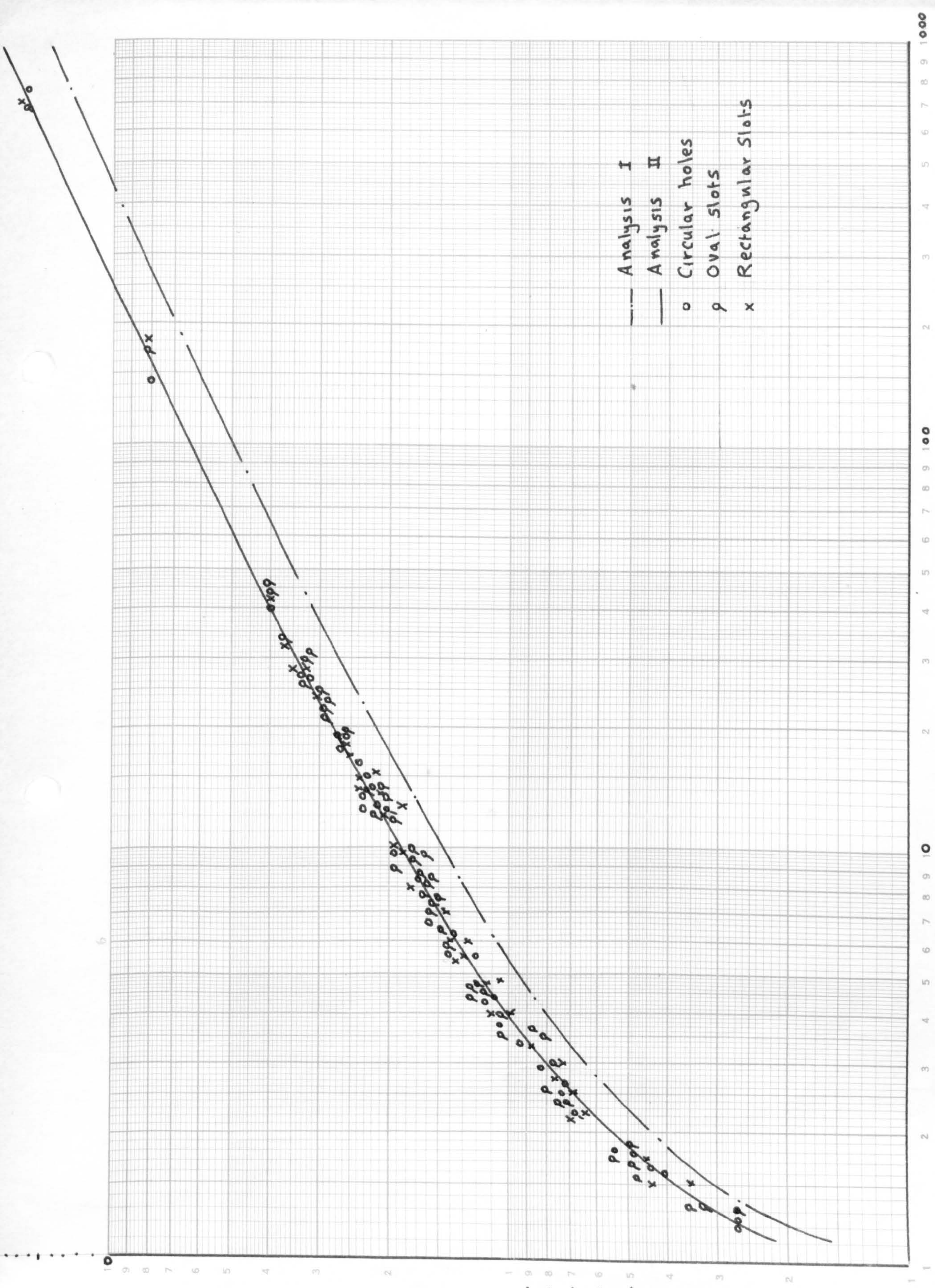


Theoretical variation of Deflection angle with flow parameter .
Flow Parameter , K

Analysis I



Variation of bleed area ratio with bleed and area ratios.



Flow Parameter : K
Variation of flow parameter with bleed area ratio .

Theoretical variation of discharge coefficient with bleed and area ratios

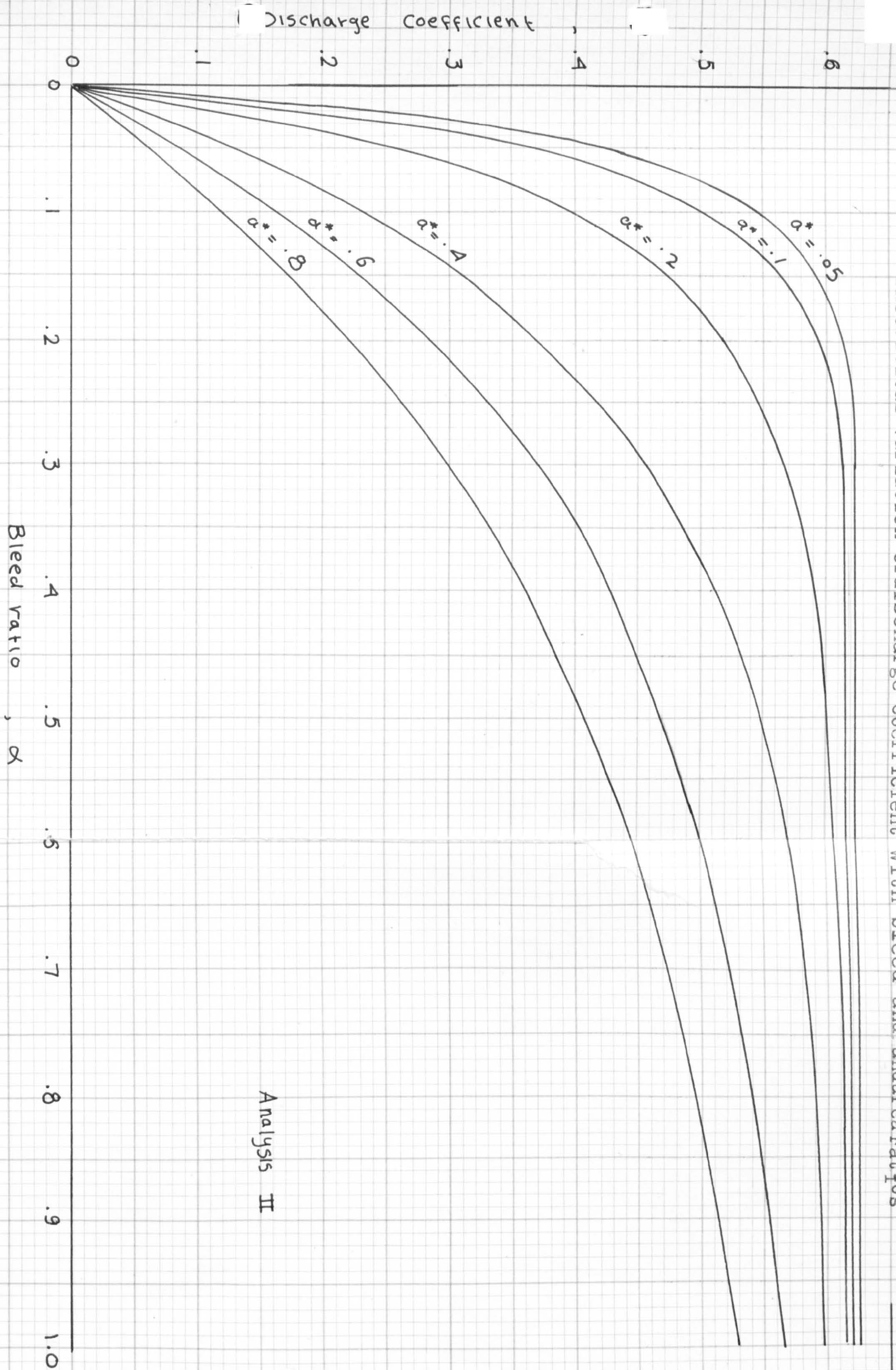
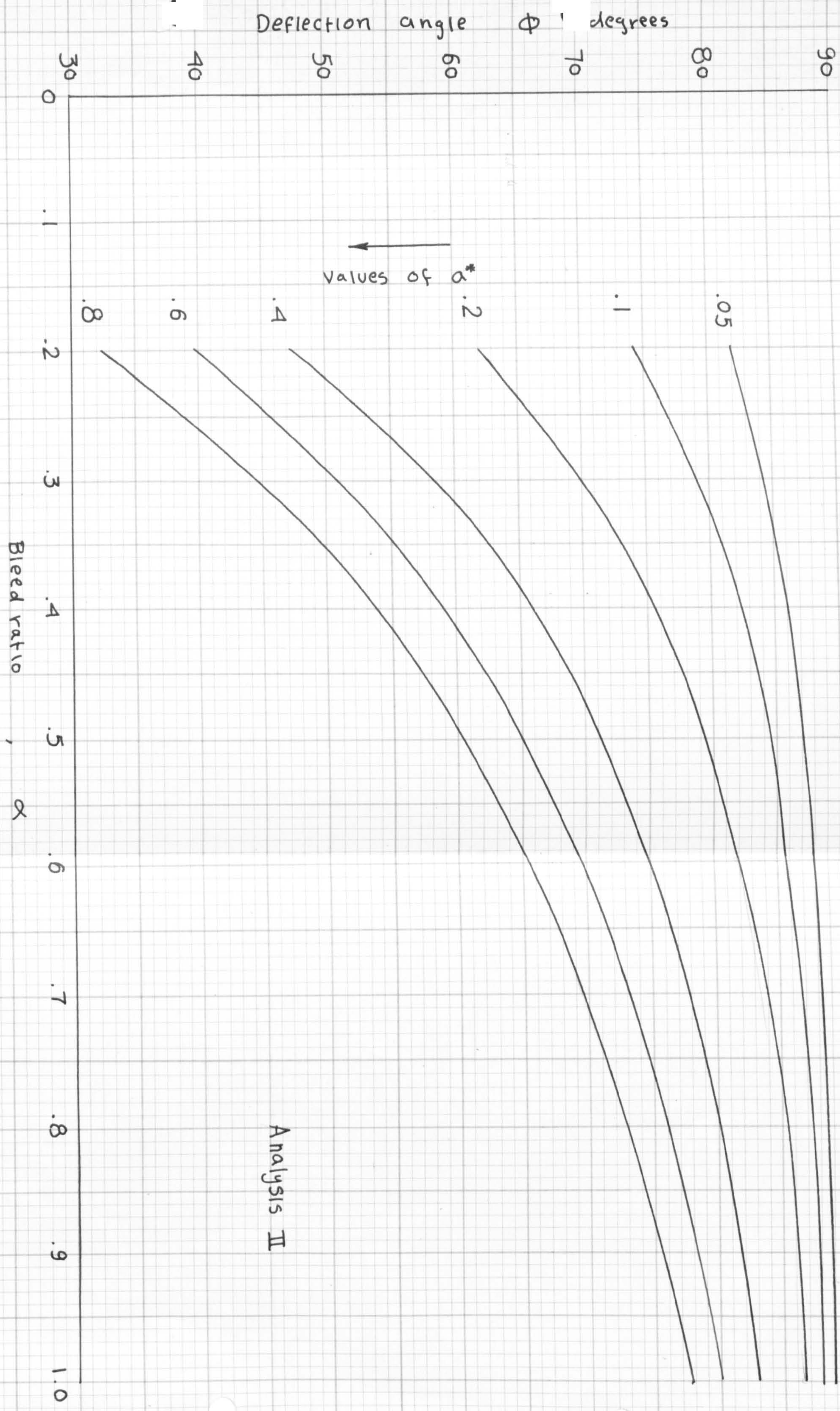
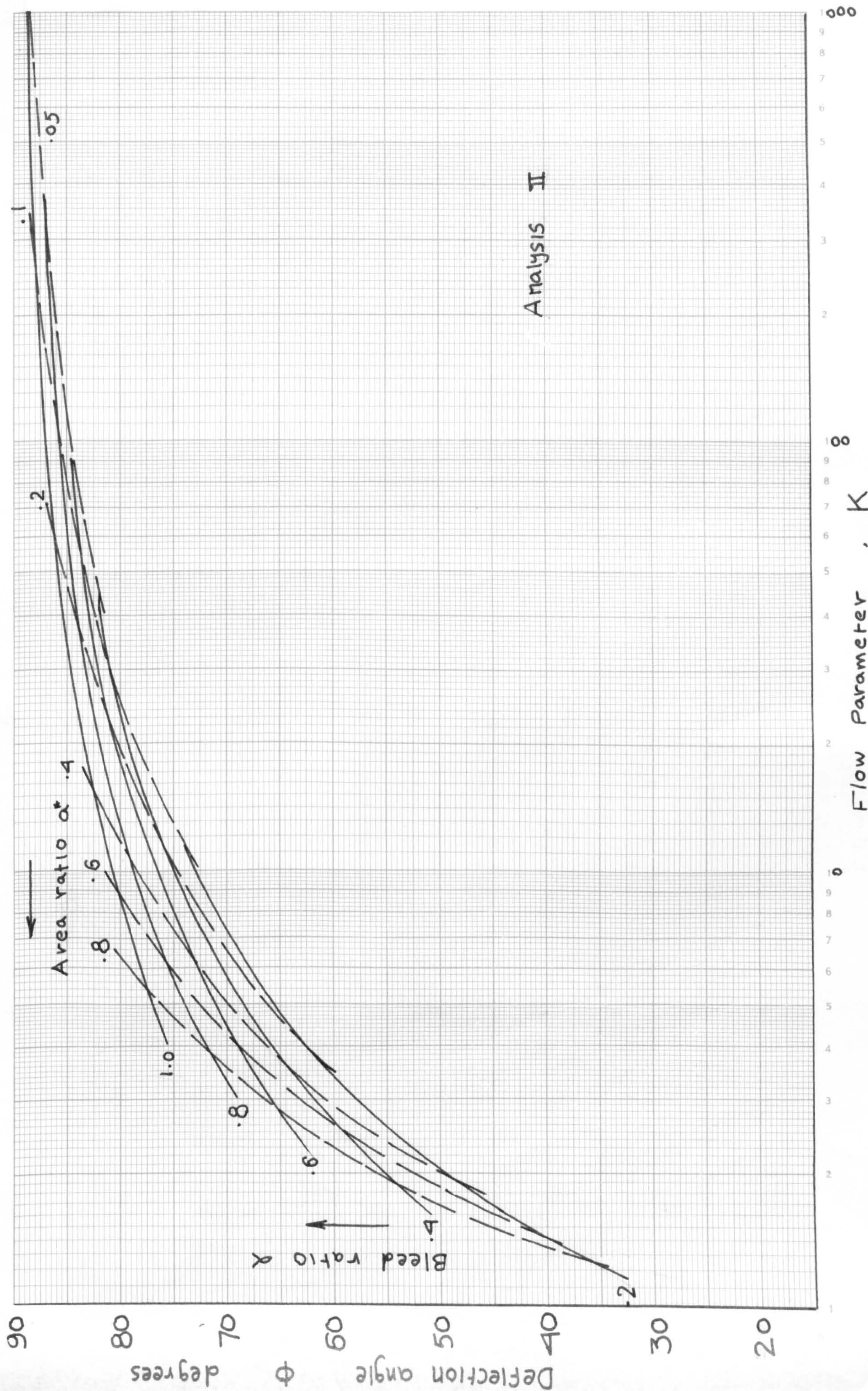


FIG. 24



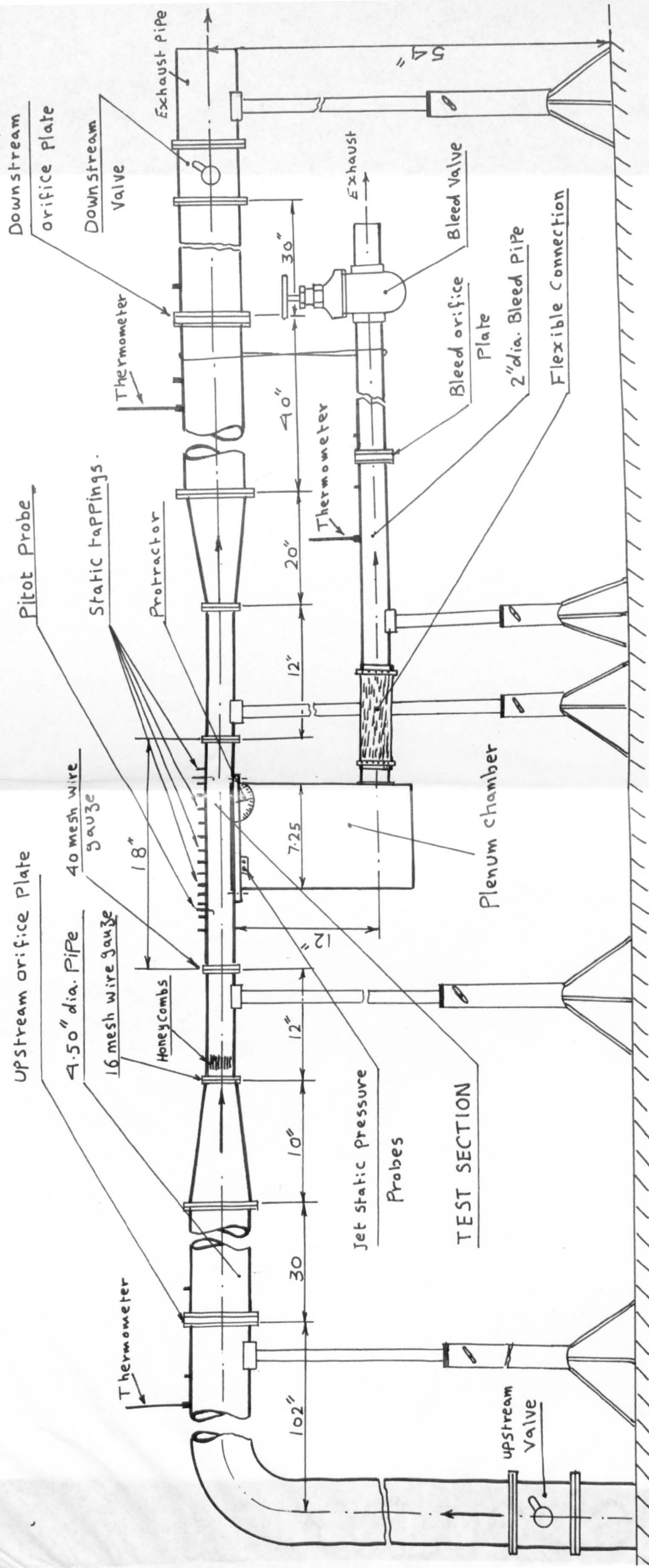
Analysis II

Theoretical variation of deflection angle with bleed and area ratios

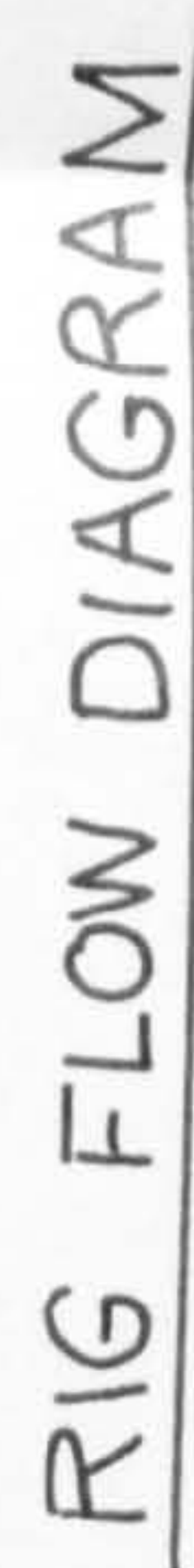


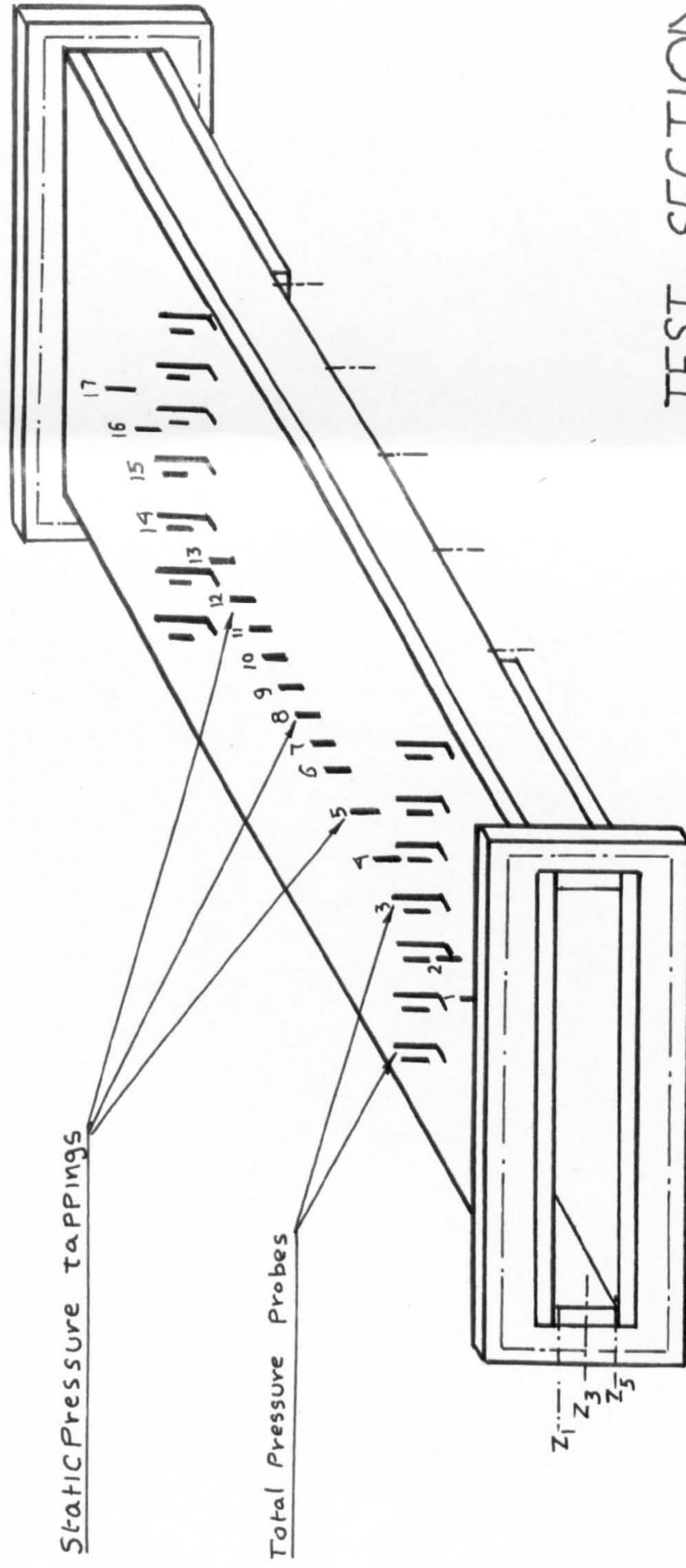
Theoretical variation of deflection angle with flow parameter

FIG. 26

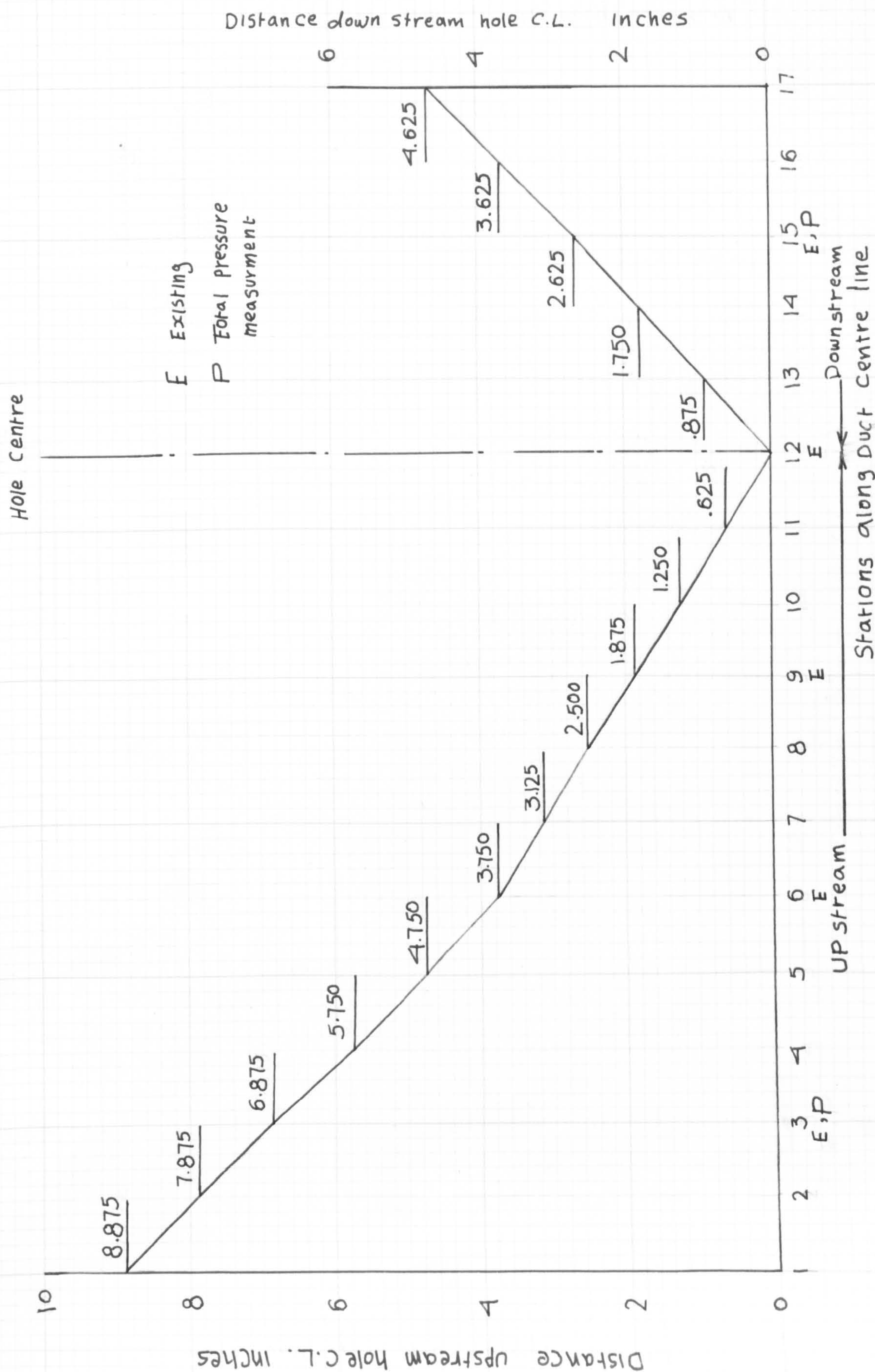


RIG LAYOUT





SCALE INCHES



Distribution of static tapplings along duct centre line opposite to holes

FIG. 29a

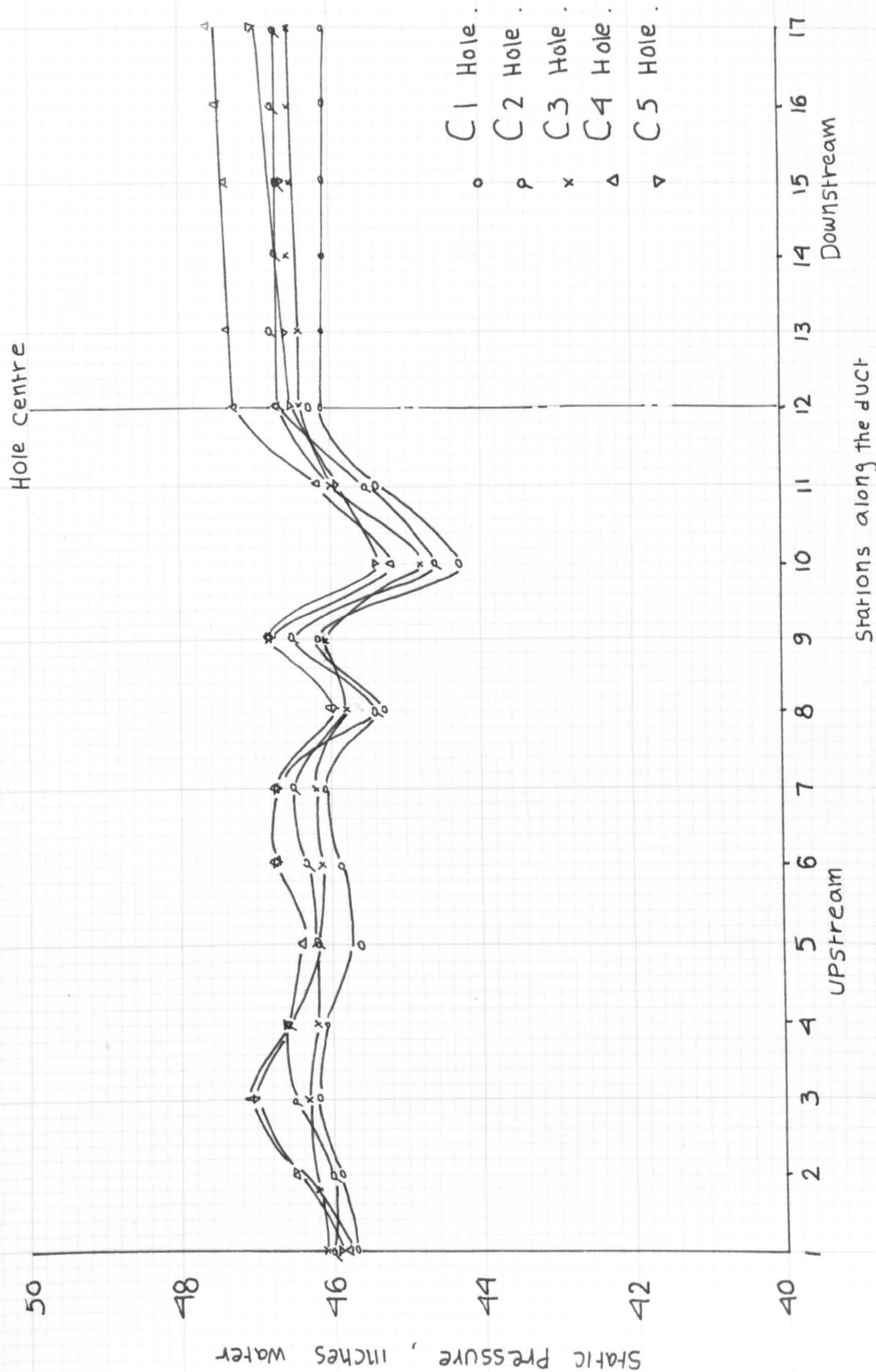
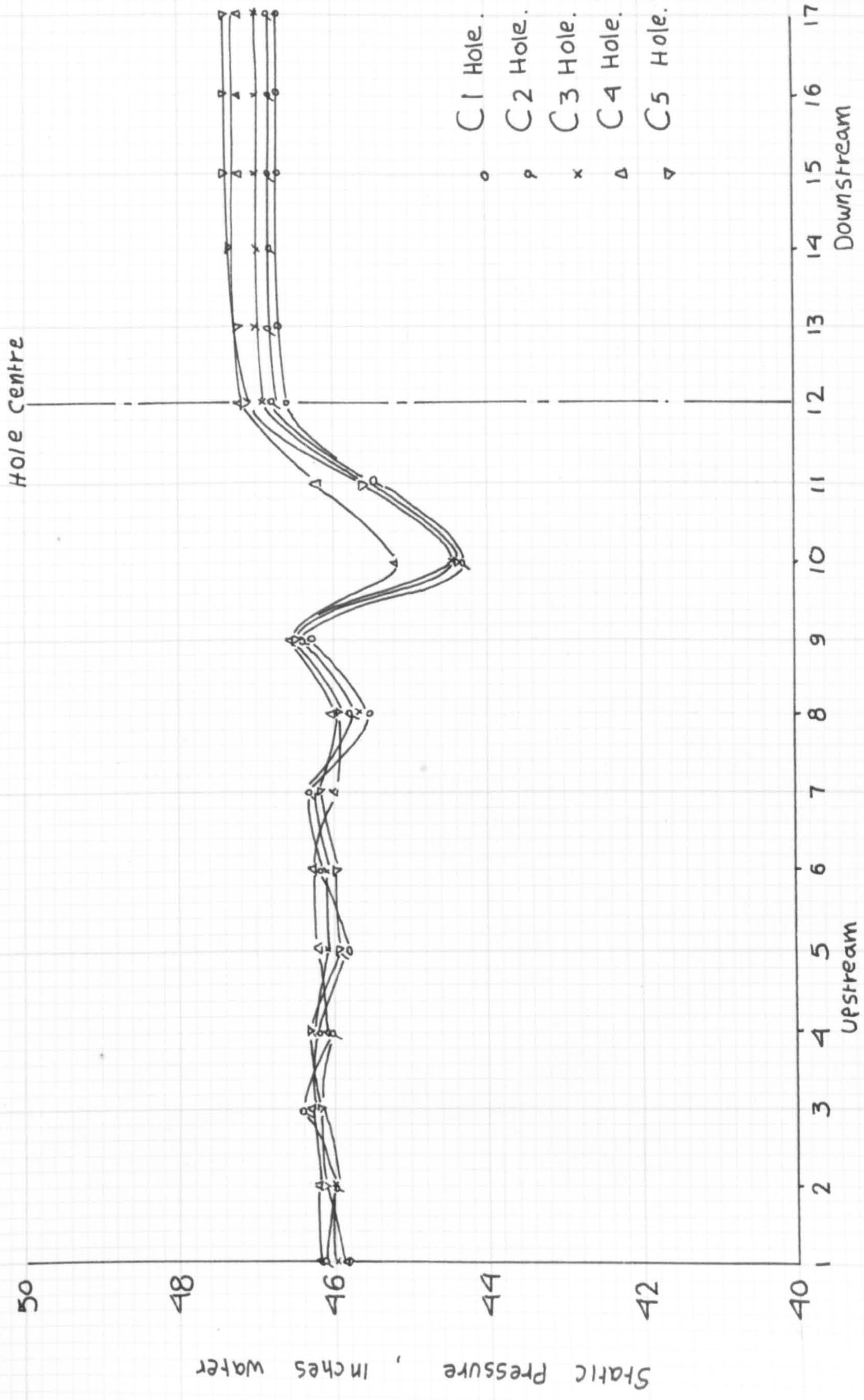


FIG. 29b



Static pressure distribution (circular holes - $V_1 = 80 \text{ ft/sec}$)

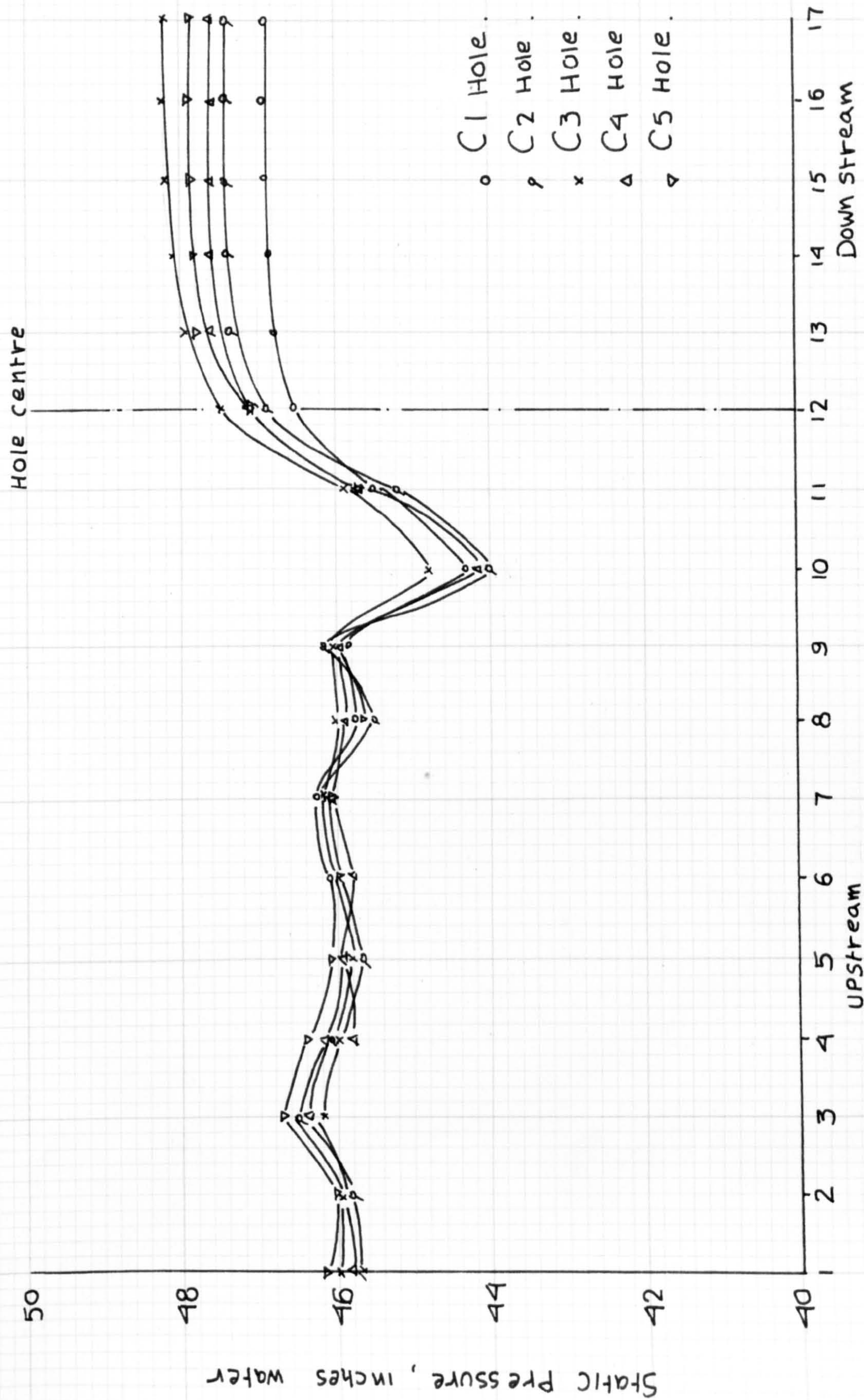
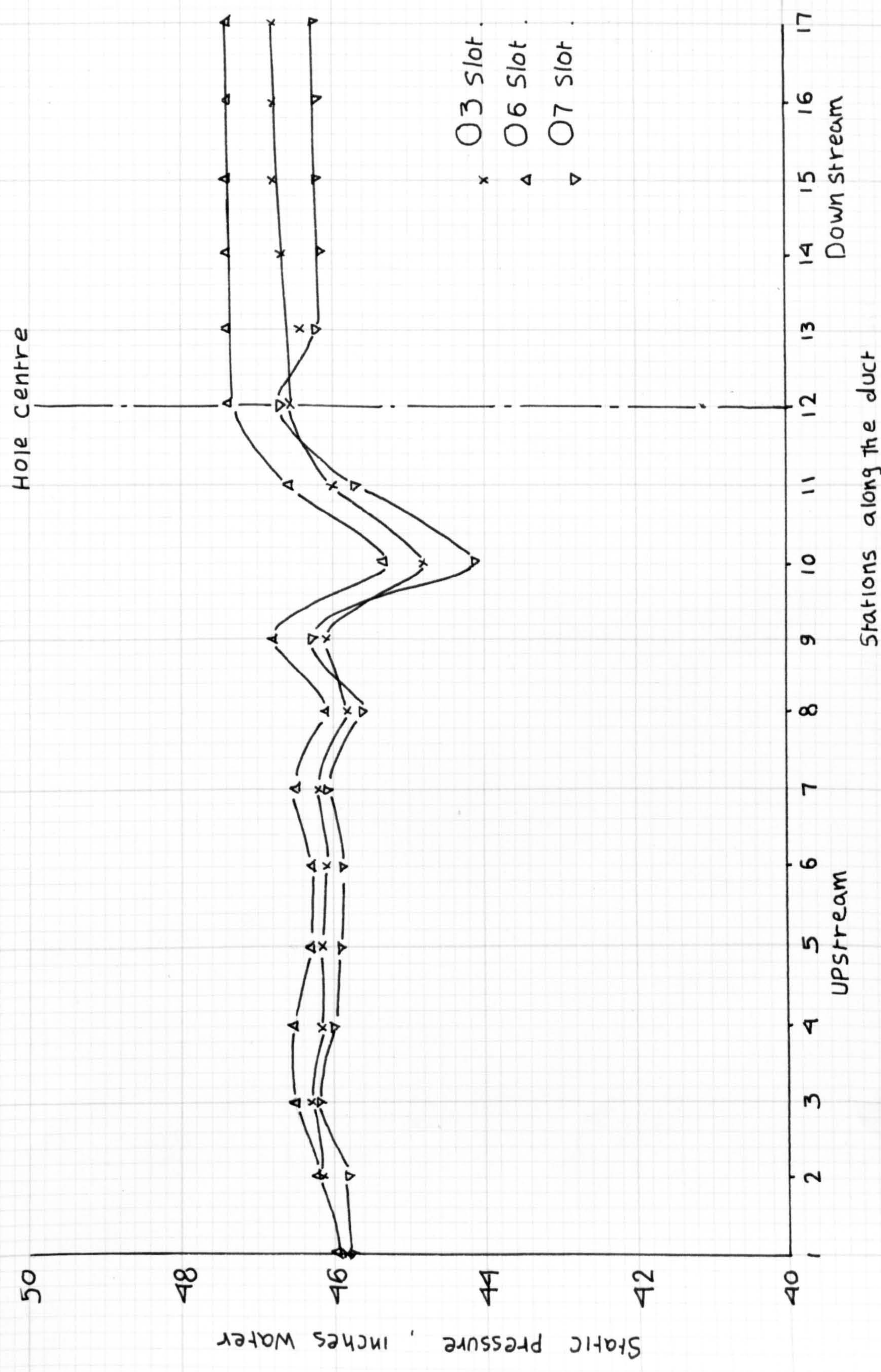


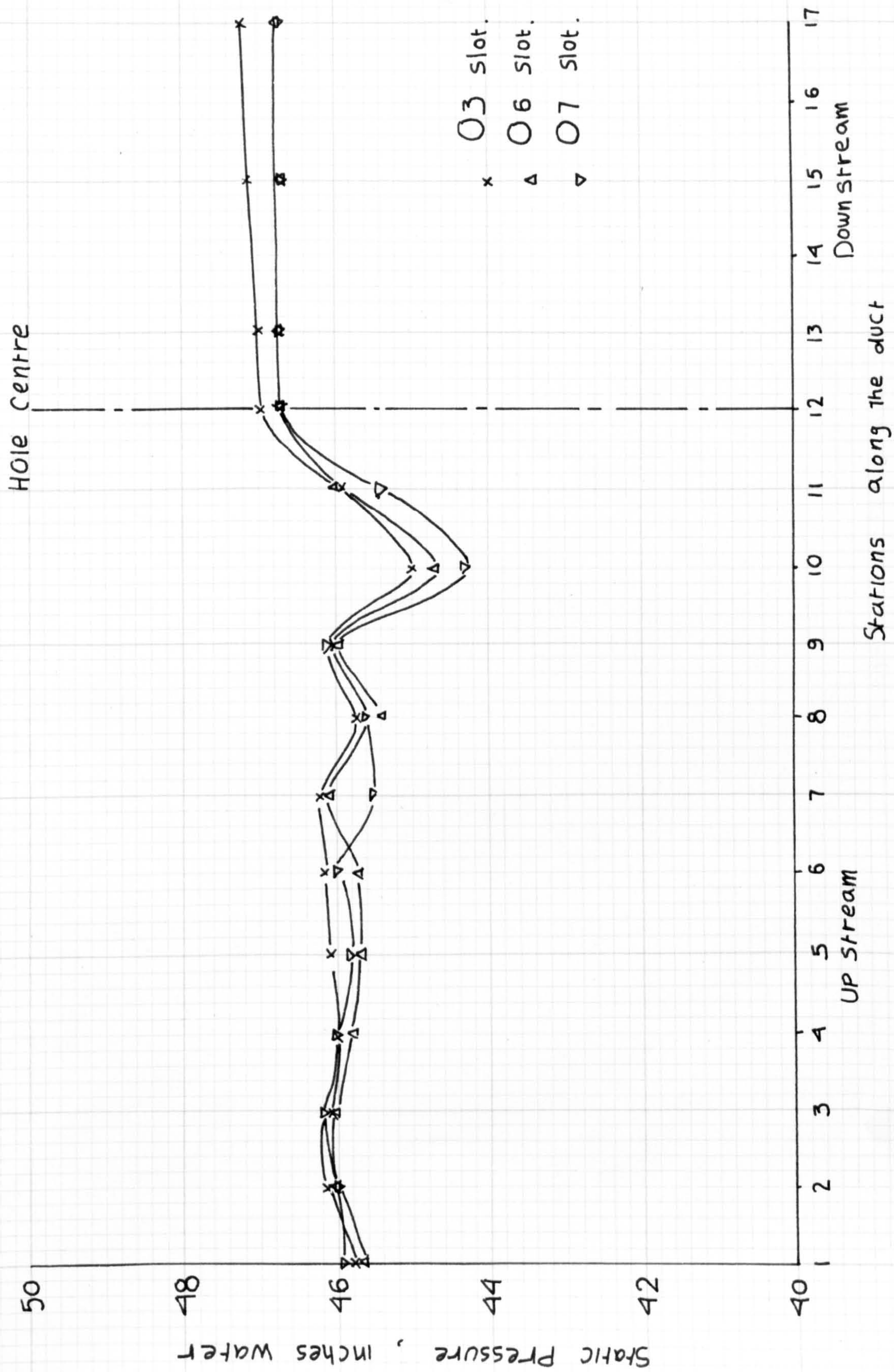
FIG.29c

Static pressure distribution (circular holes - Approach velocity = 130ft/sec)

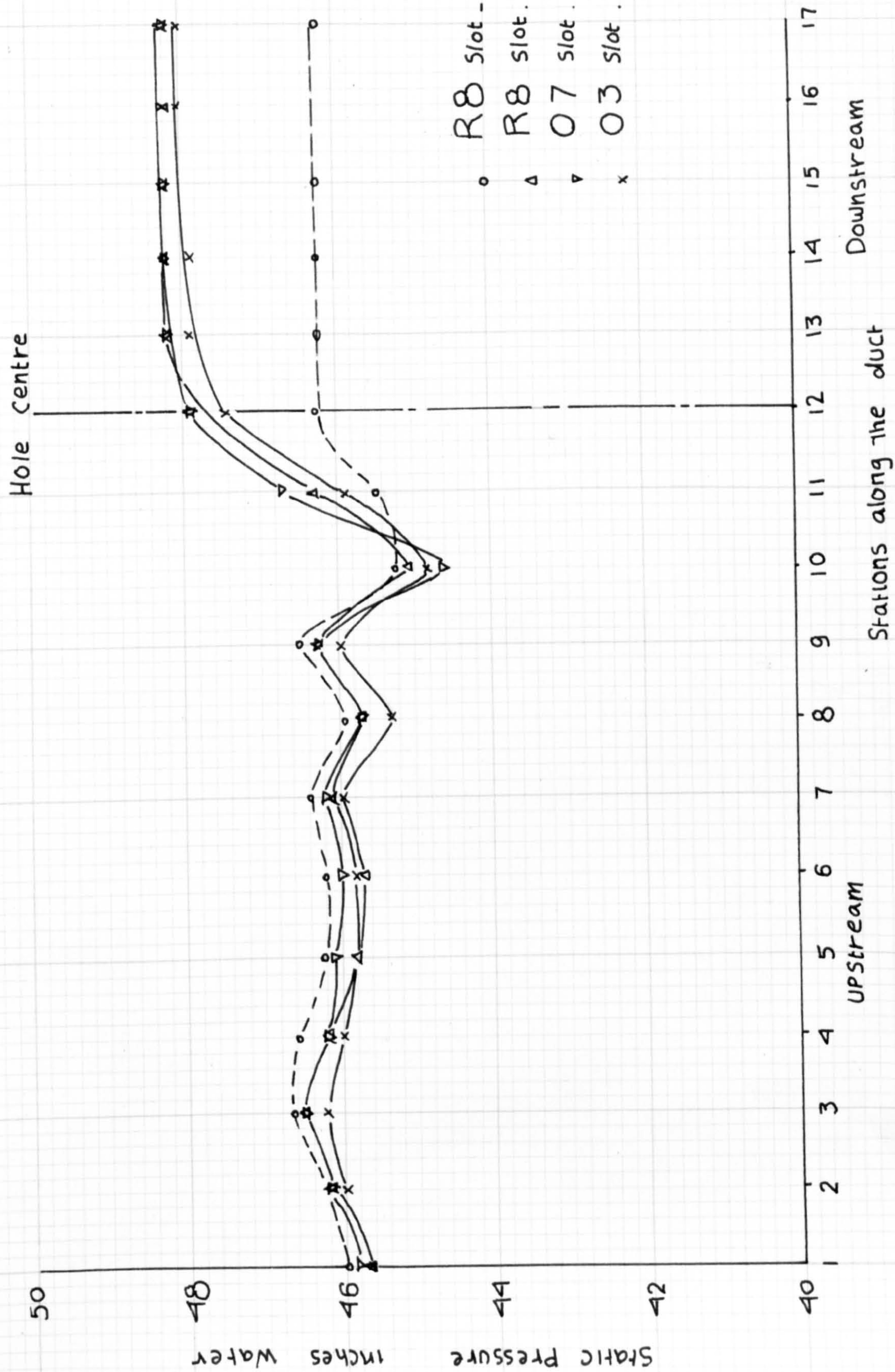
FIG. 29d



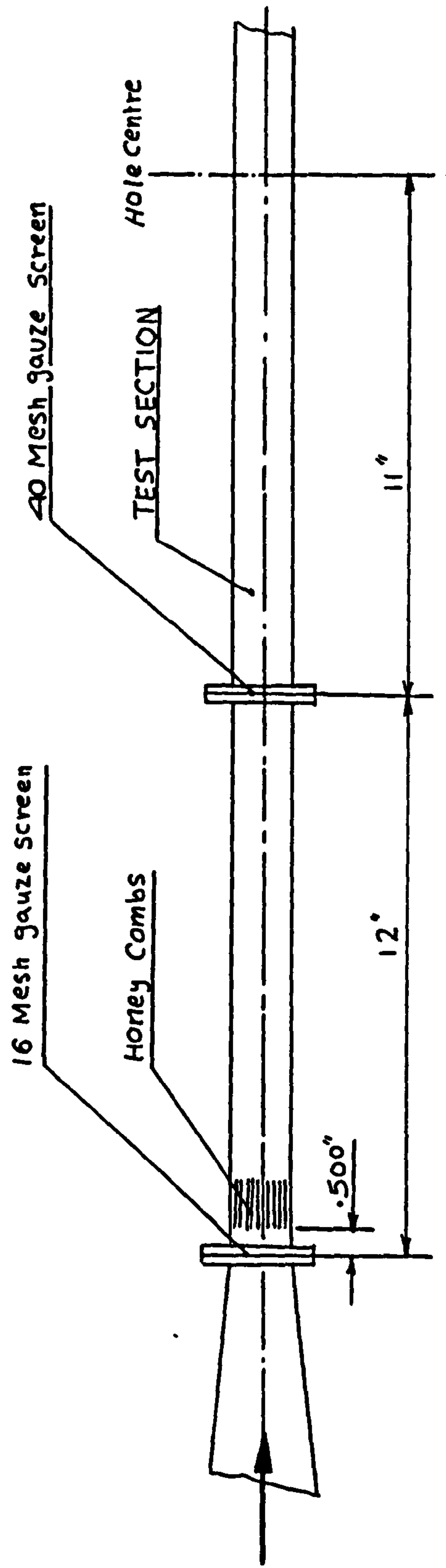
Static pressure distribution (oval slots -No cross flow)



Static pressure distribution (oval slots - $V_1 = 80$ ft/sec)

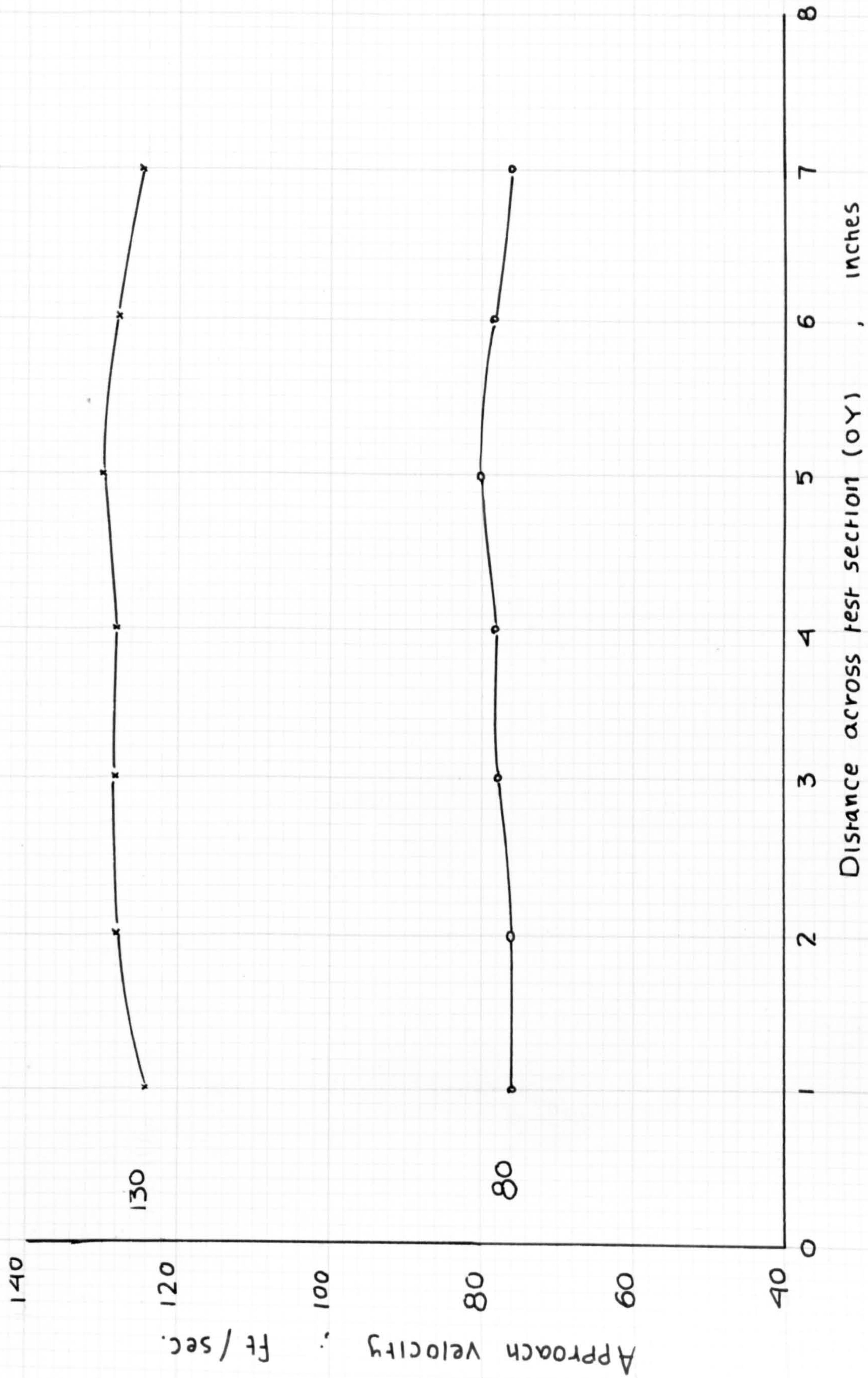


Static pressure distribution (Oval slots $V_1 = 130$ ft/sec)

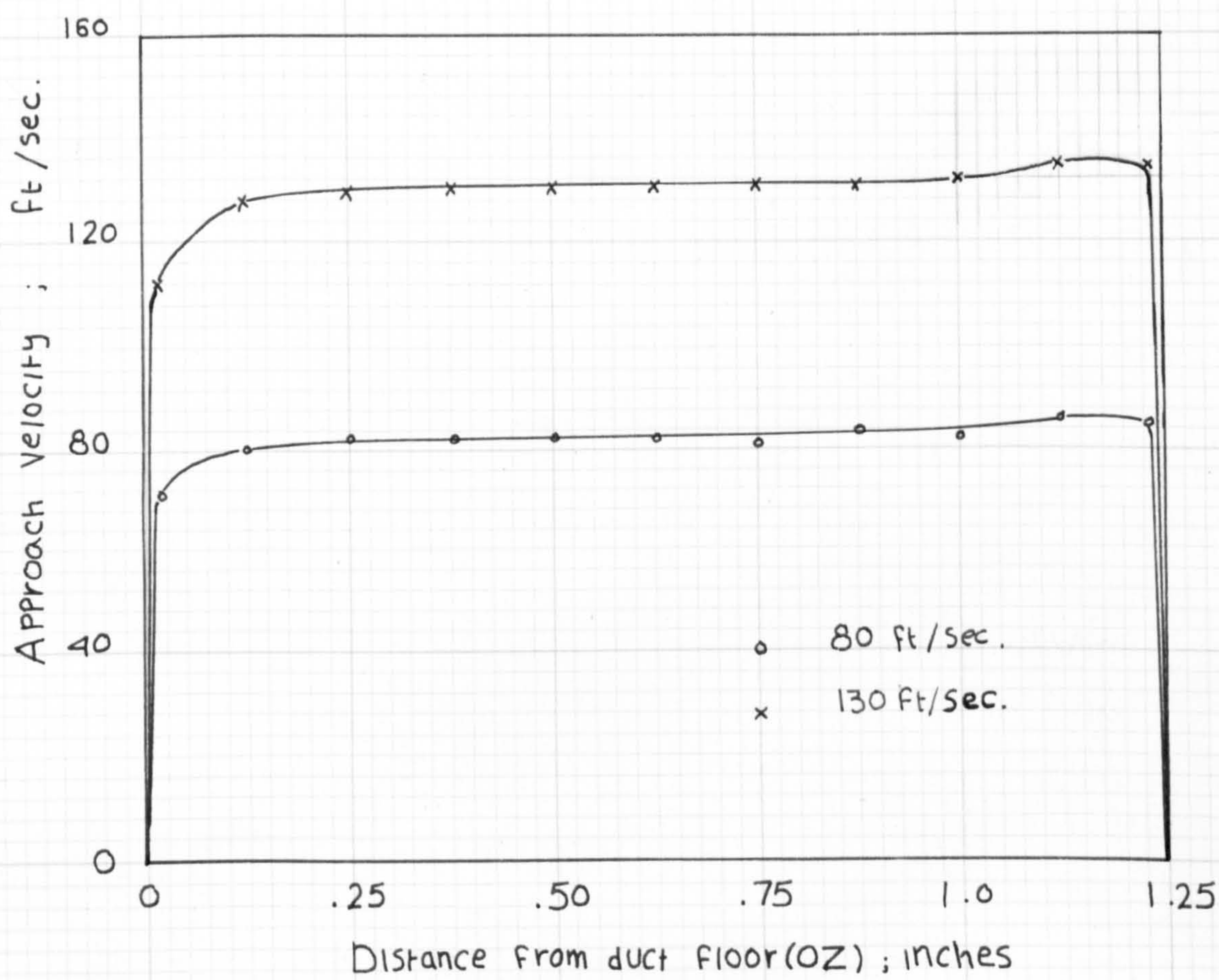


Mesh screen arrangement in the approach duct

FIG. 31



Approach velocity distribution across test section(OY)



Velocity profile across test section (OZ)

48

47

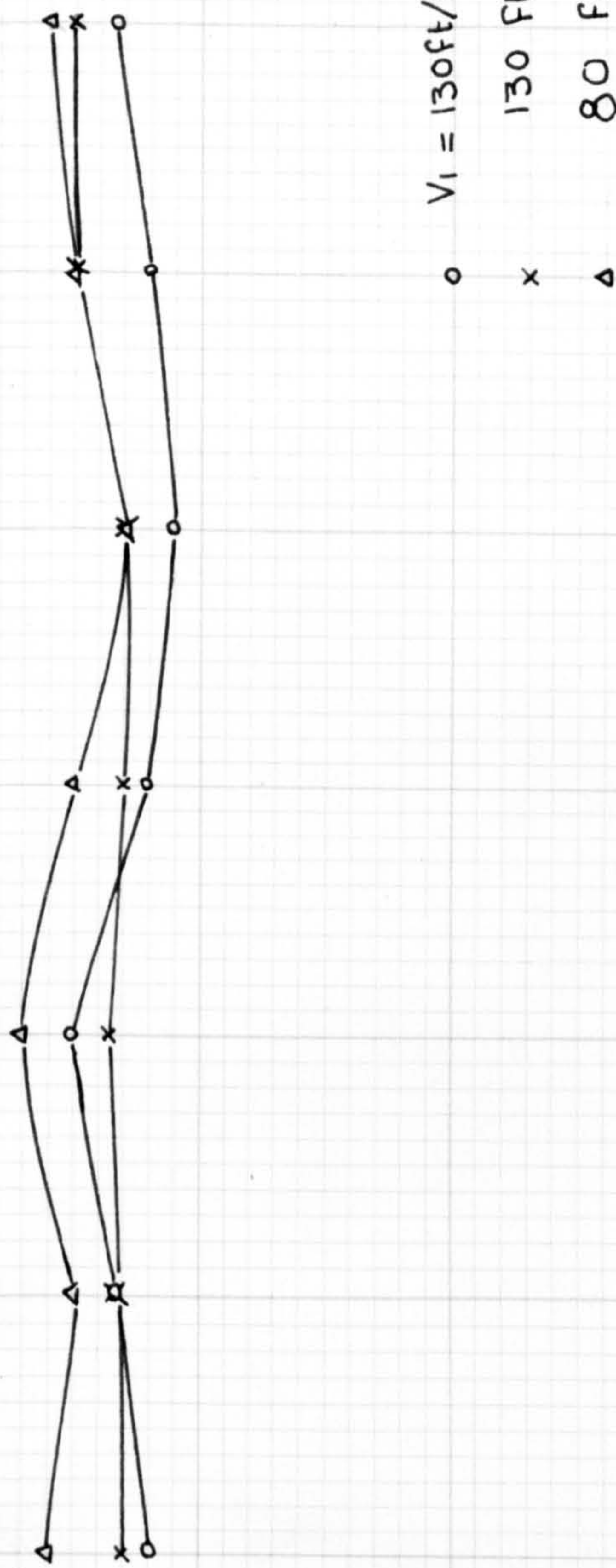
46

45

44

43

Approach static pressure, inches water

O $V_1 = 130 \text{ ft/sec}$ (No test holes)

X 130 ft/sec (With test holes)

Δ 80 ft/sec.

8

7

6

5

4

3

2

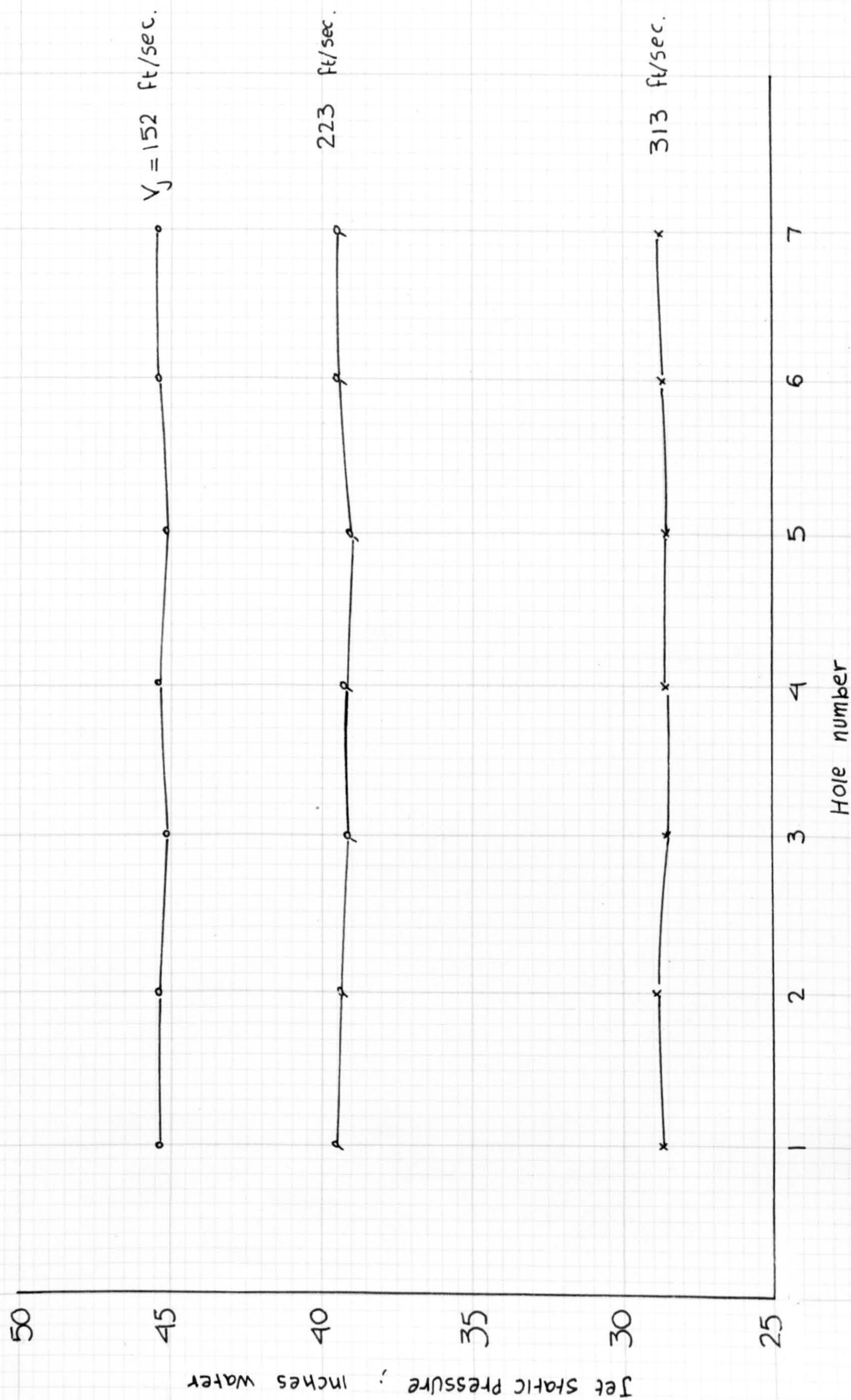
1

0

Distance across test section (OY) ; inches

Approach static pressure distribution across test section(OY)

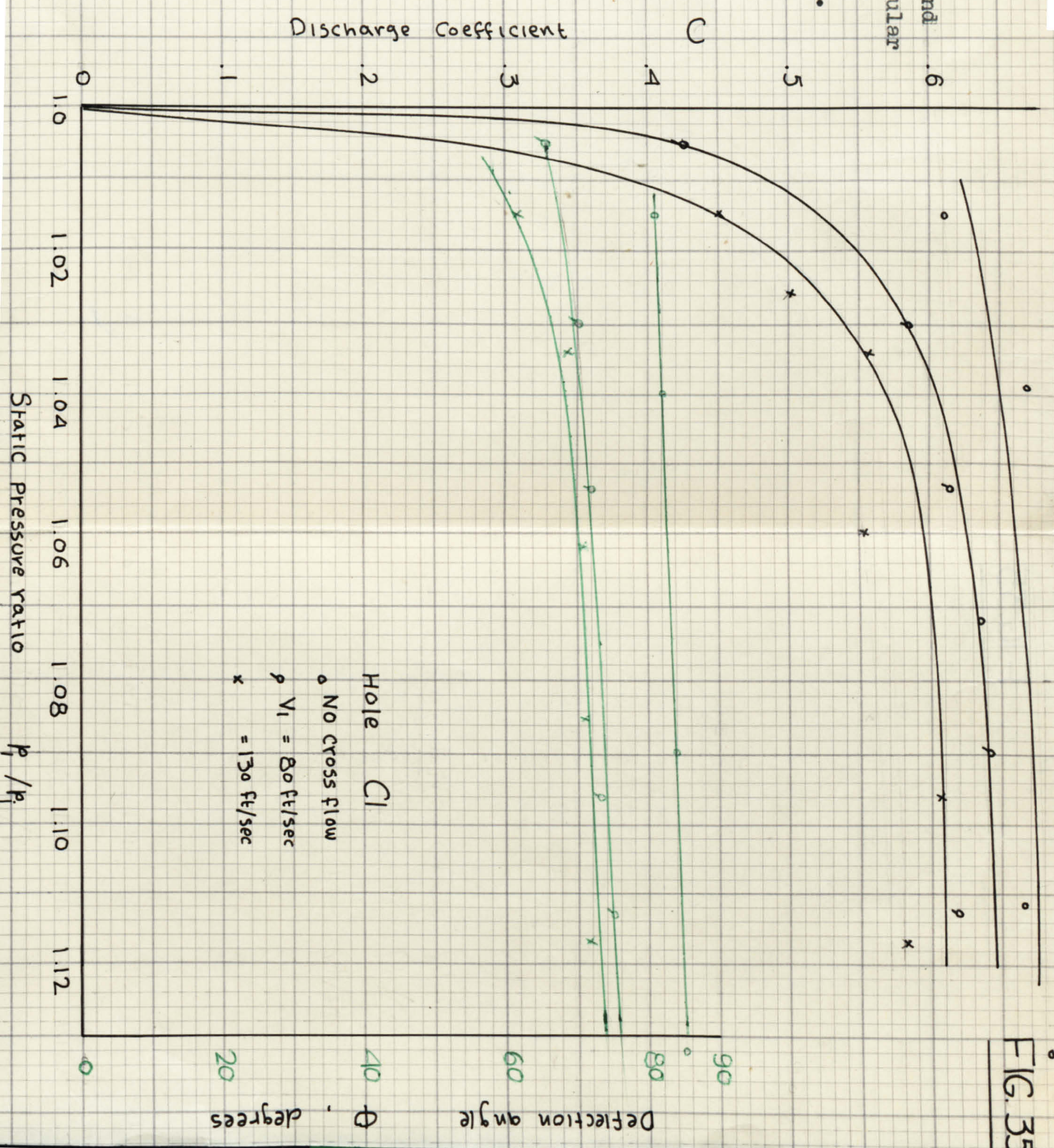
FIG. 33



Jet static pressure distribution over 7 test holes

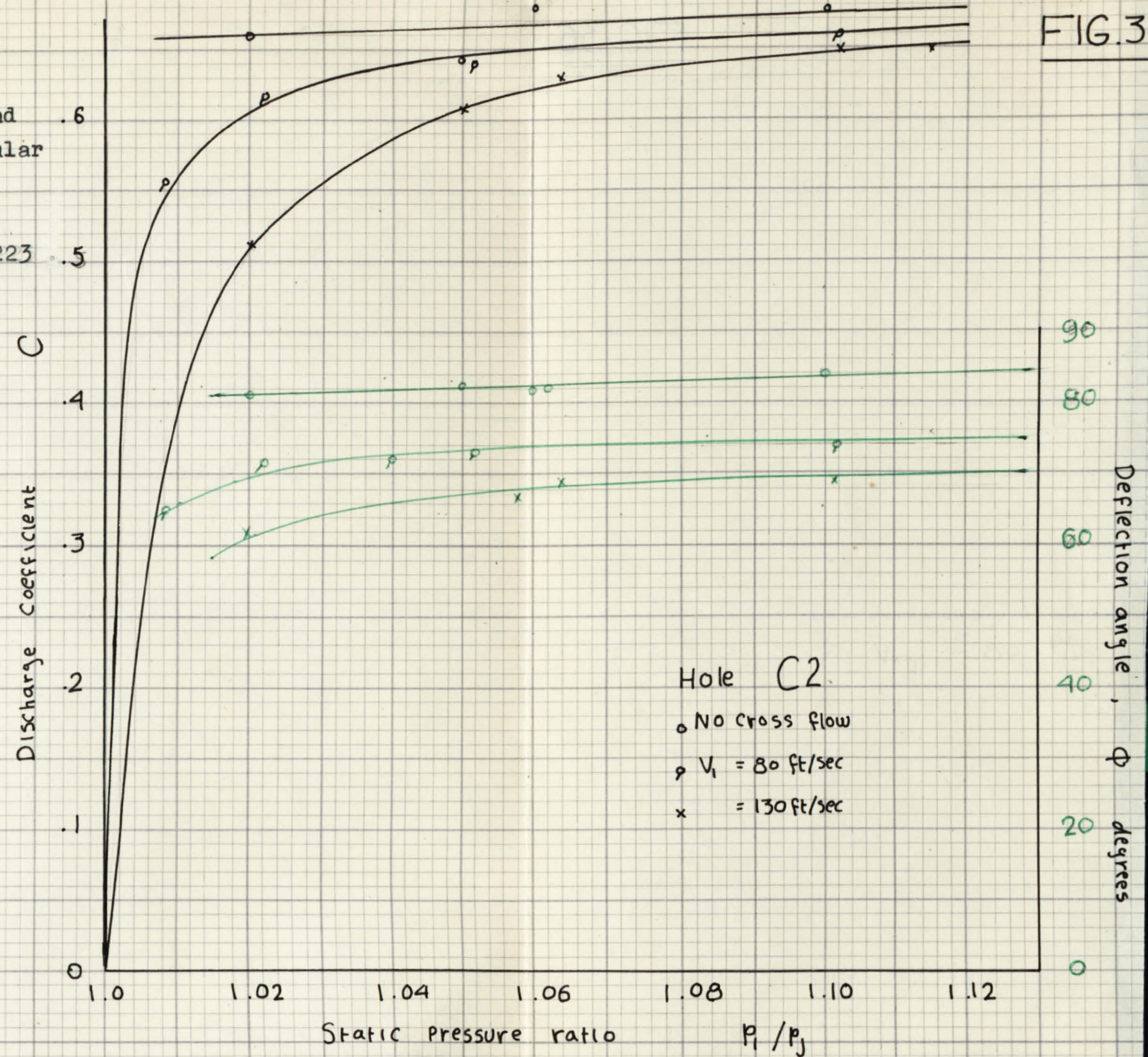
FIG. 35

Discharge coefficient and
jet Deflection for circular
holes.
 $D = .328 \text{ in.}$, $x^* = .0595$.



Discharge coefficient and
jet deflection for circular
holes.

$D = 0.472$ in. , $a^* = 0.1223$



Hole C2
 ○ No cross flow
 p $V_1 = 80$ ft/sec
 x $V_1 = 130$ ft/sec

Discharge coefficient and
jet deflection for circular
holes.

$D = 0.807 \text{ in.}$, $a^* = 0.2542$

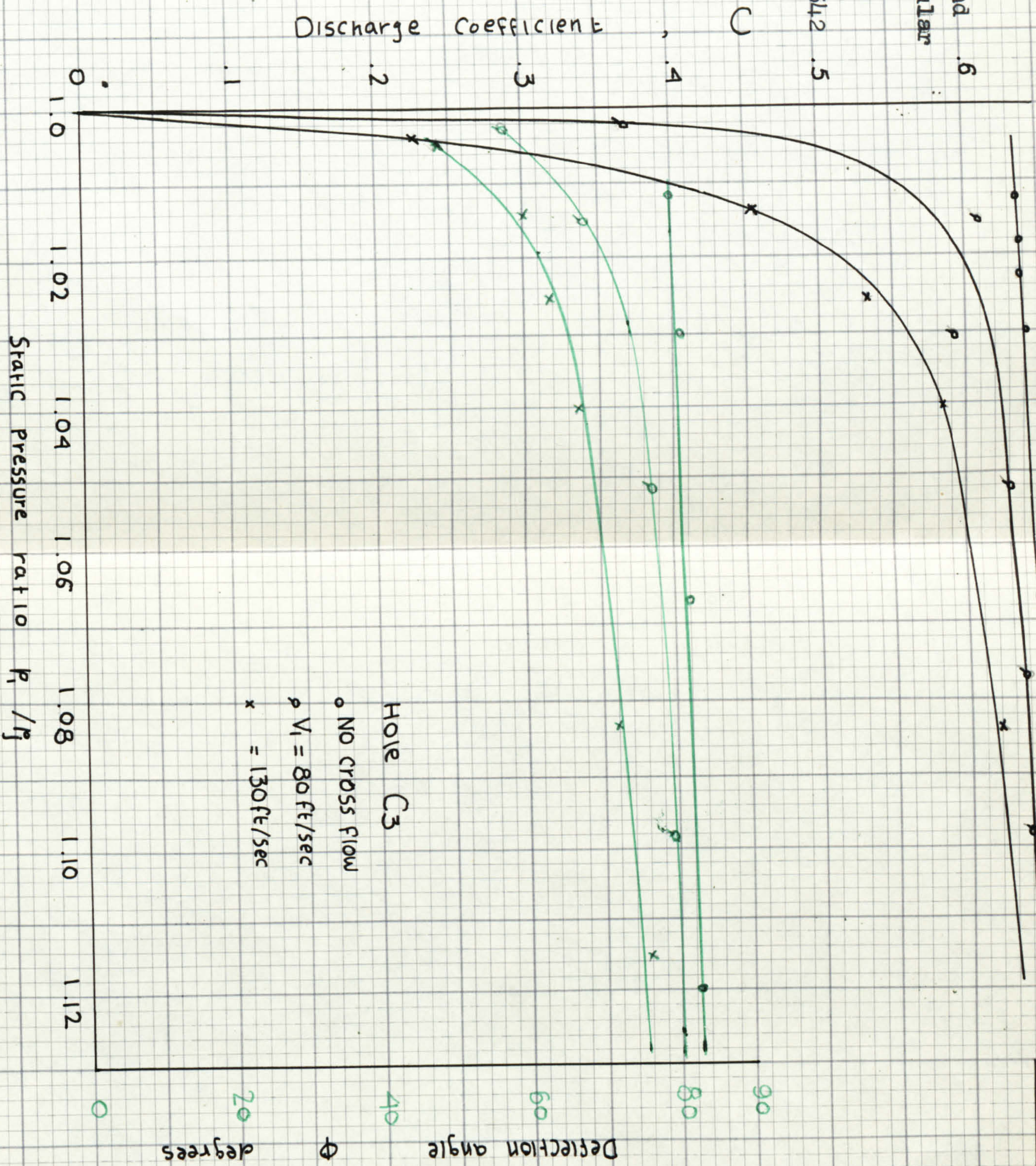
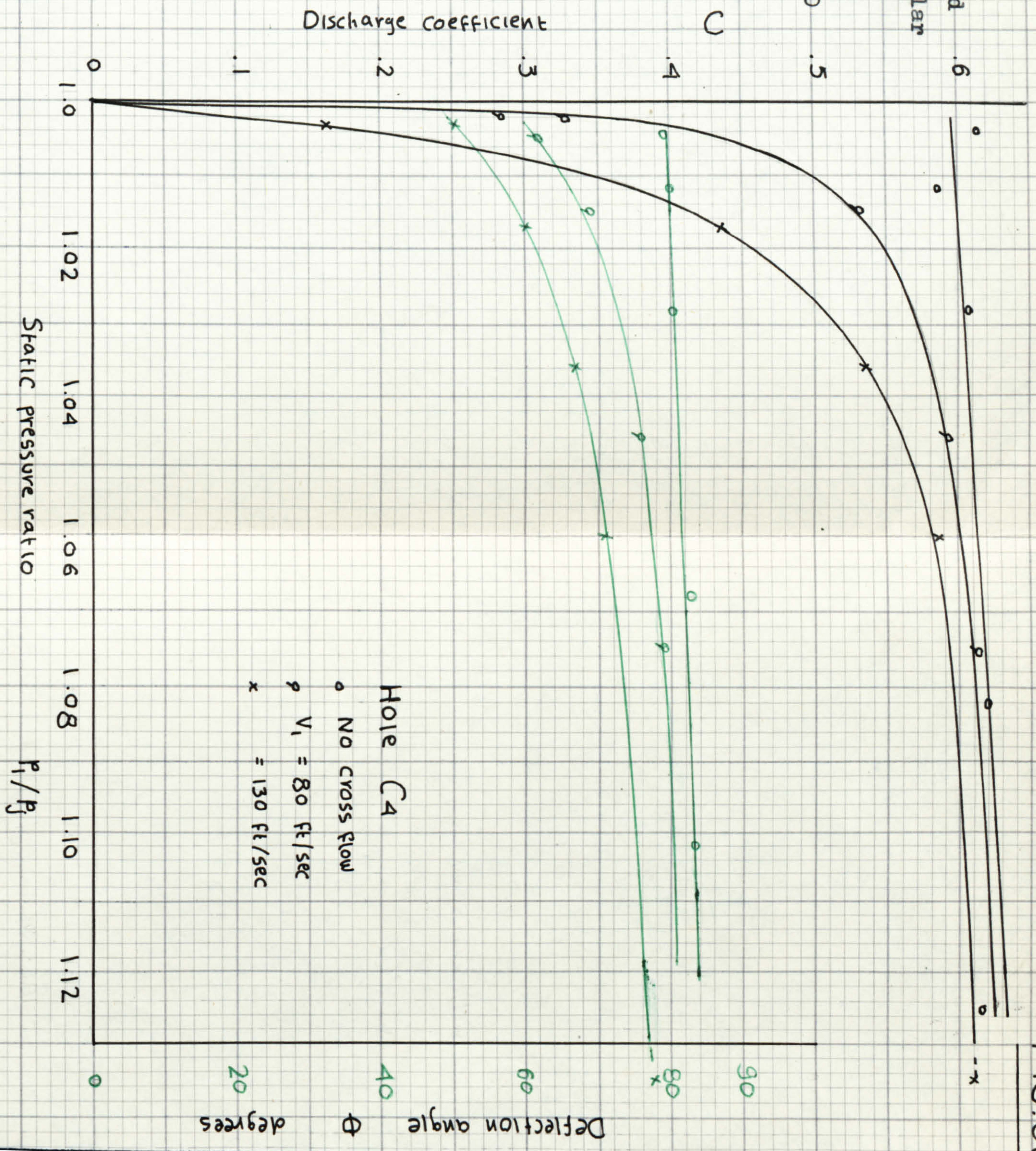


FIG. 38

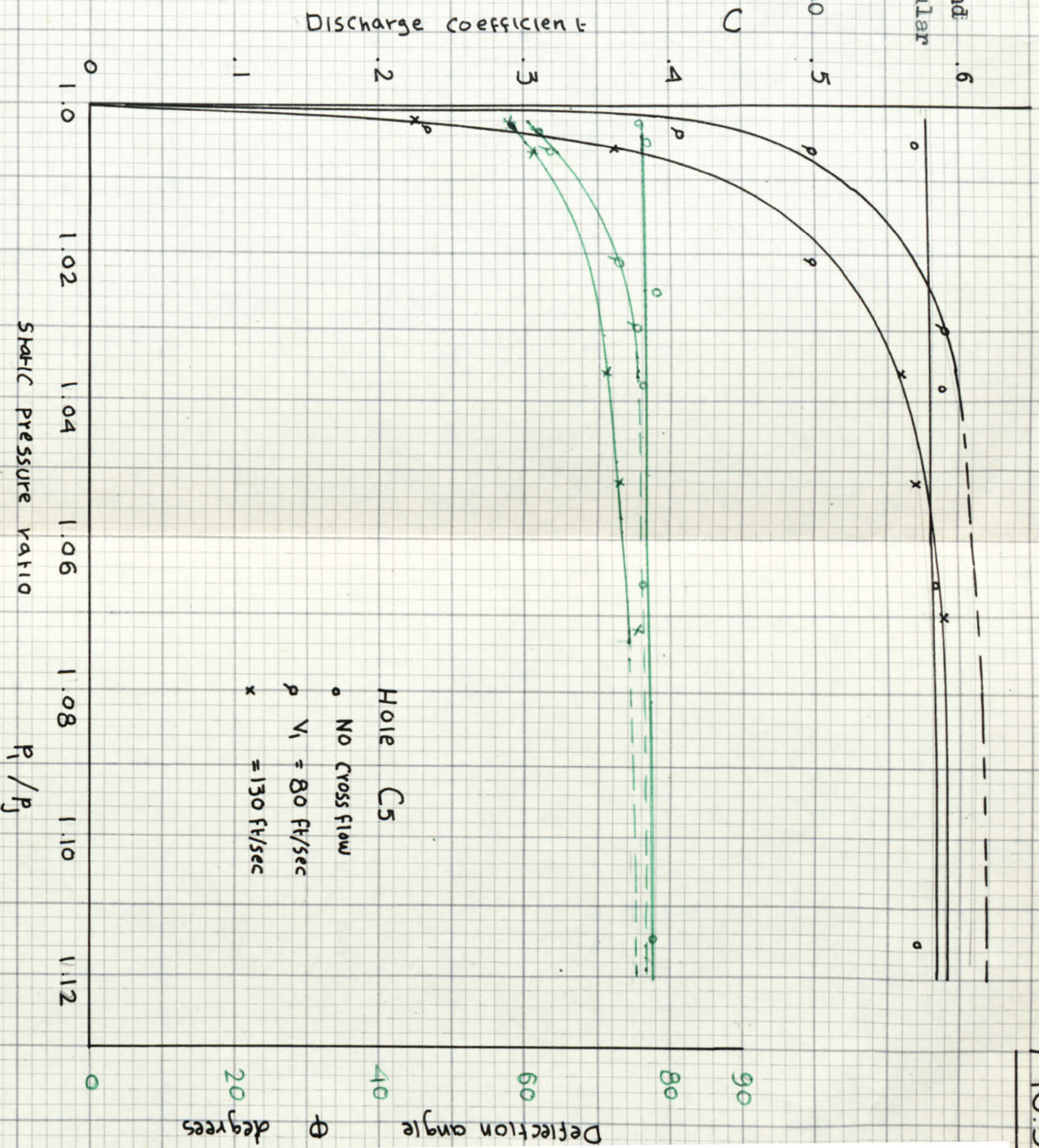
Discharge coefficient and
jet deflection for circular
holes.

$D = 0.985 \text{ in.}$, $a^* = 0.3810$



Discharge coefficient and
jet deflection for circular
holes.

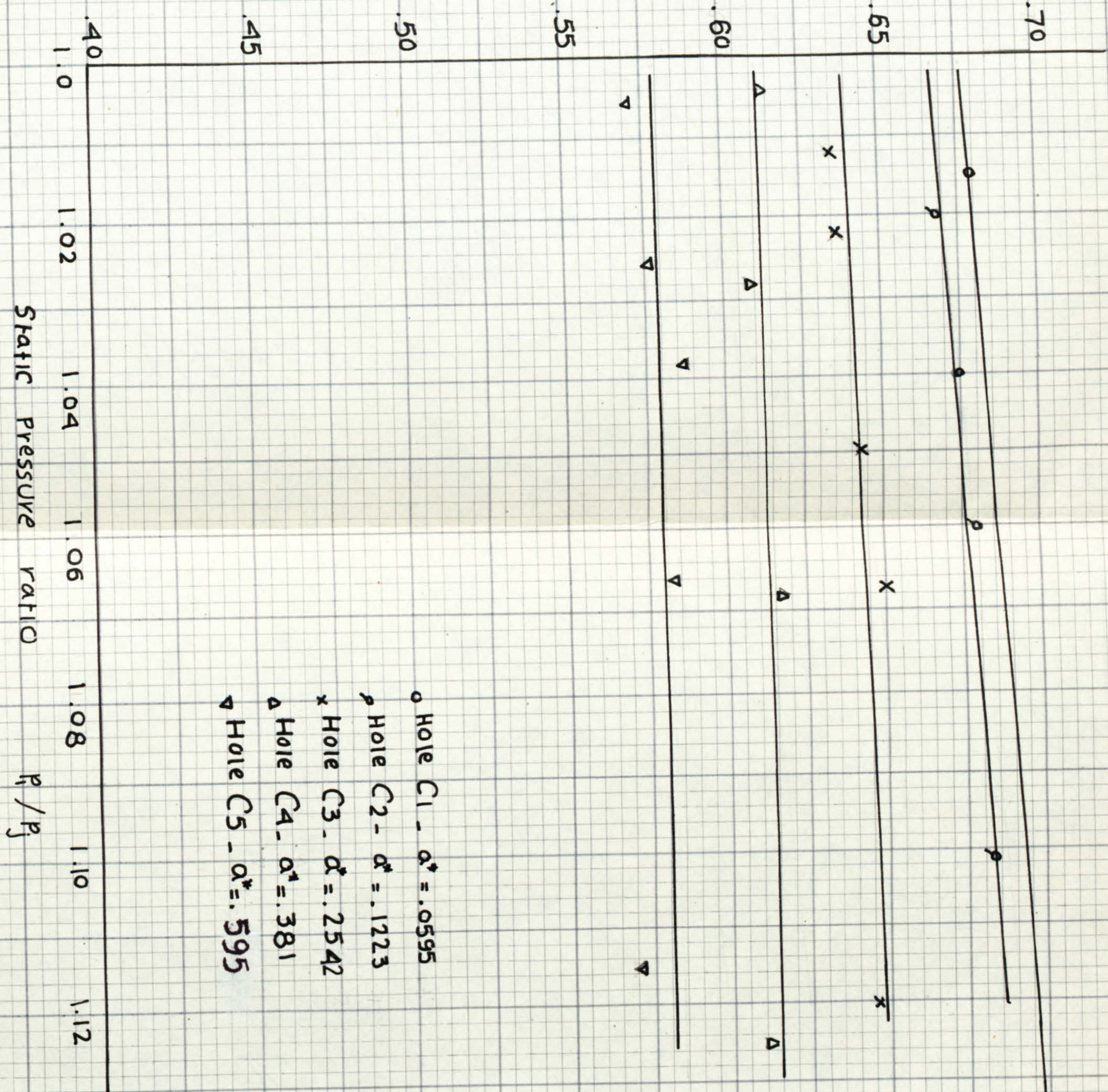
$D = 1.590 \text{ in.}$, $a^* = 0.5950$



Discharge coefficient for
circular holes •

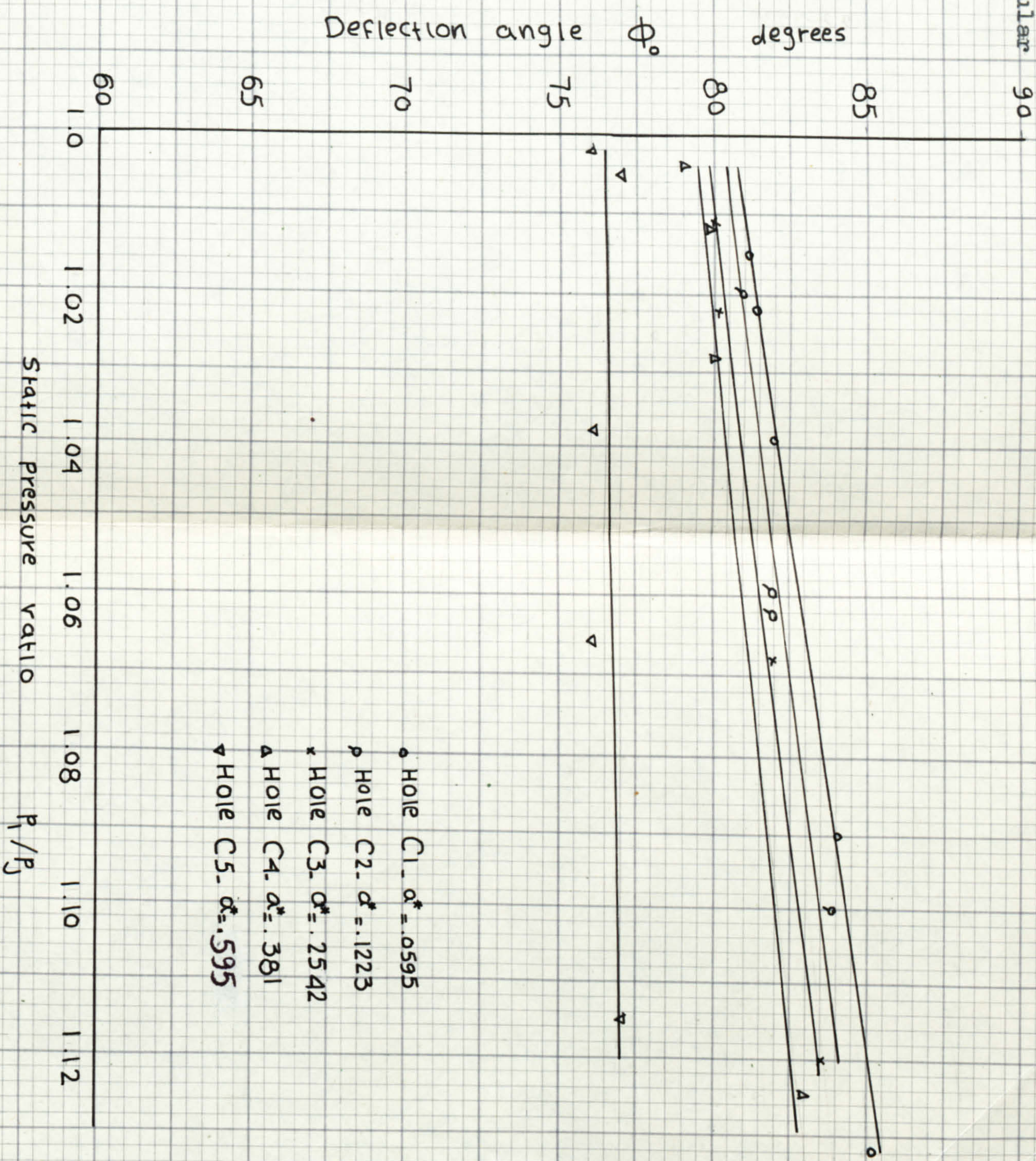
No cross flow •

Discharge coefficient



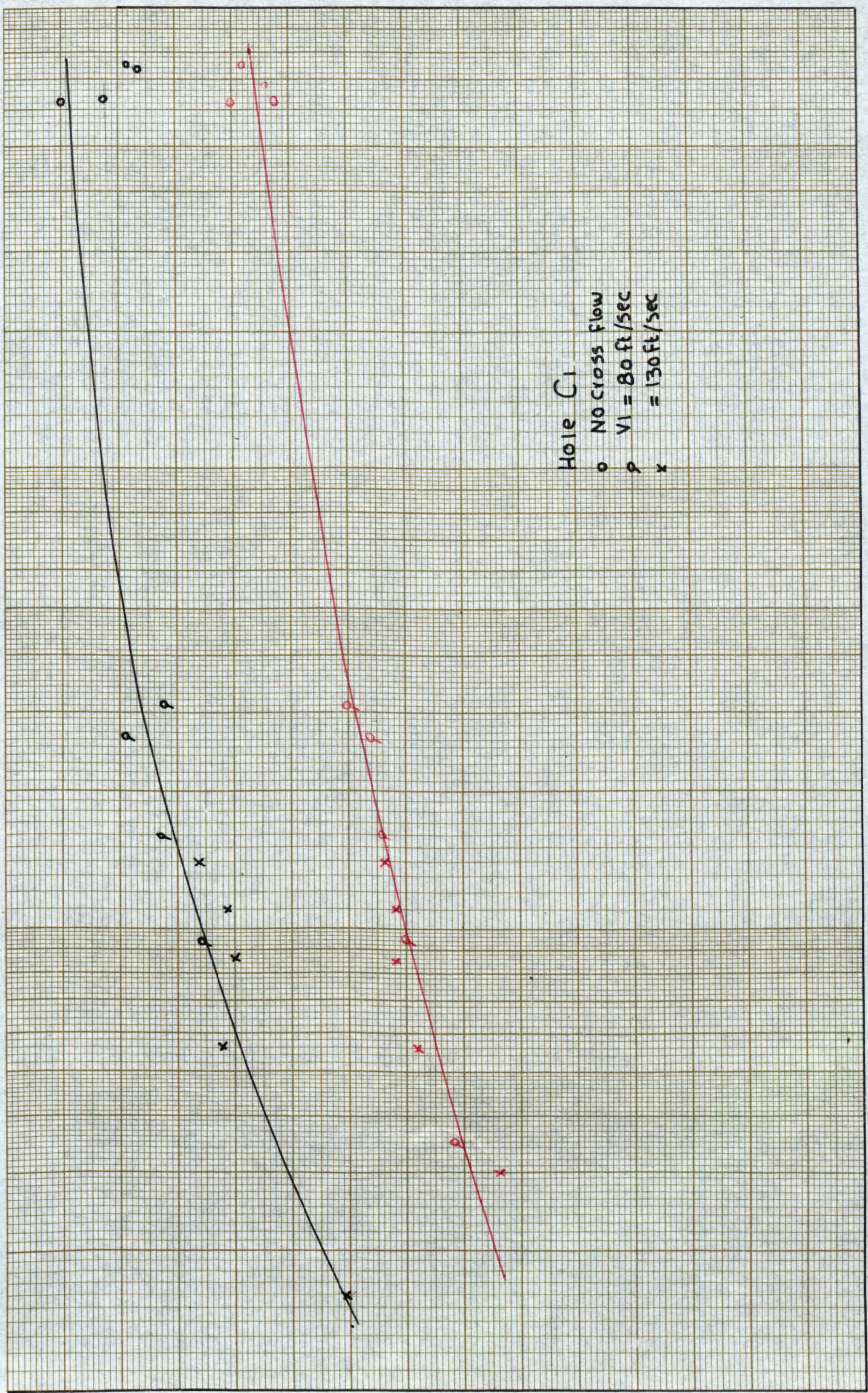
Jet deflection for circular
holes •

No cross flow •



Deflection angle ϕ degrees

90 80 70 60 50 40 30

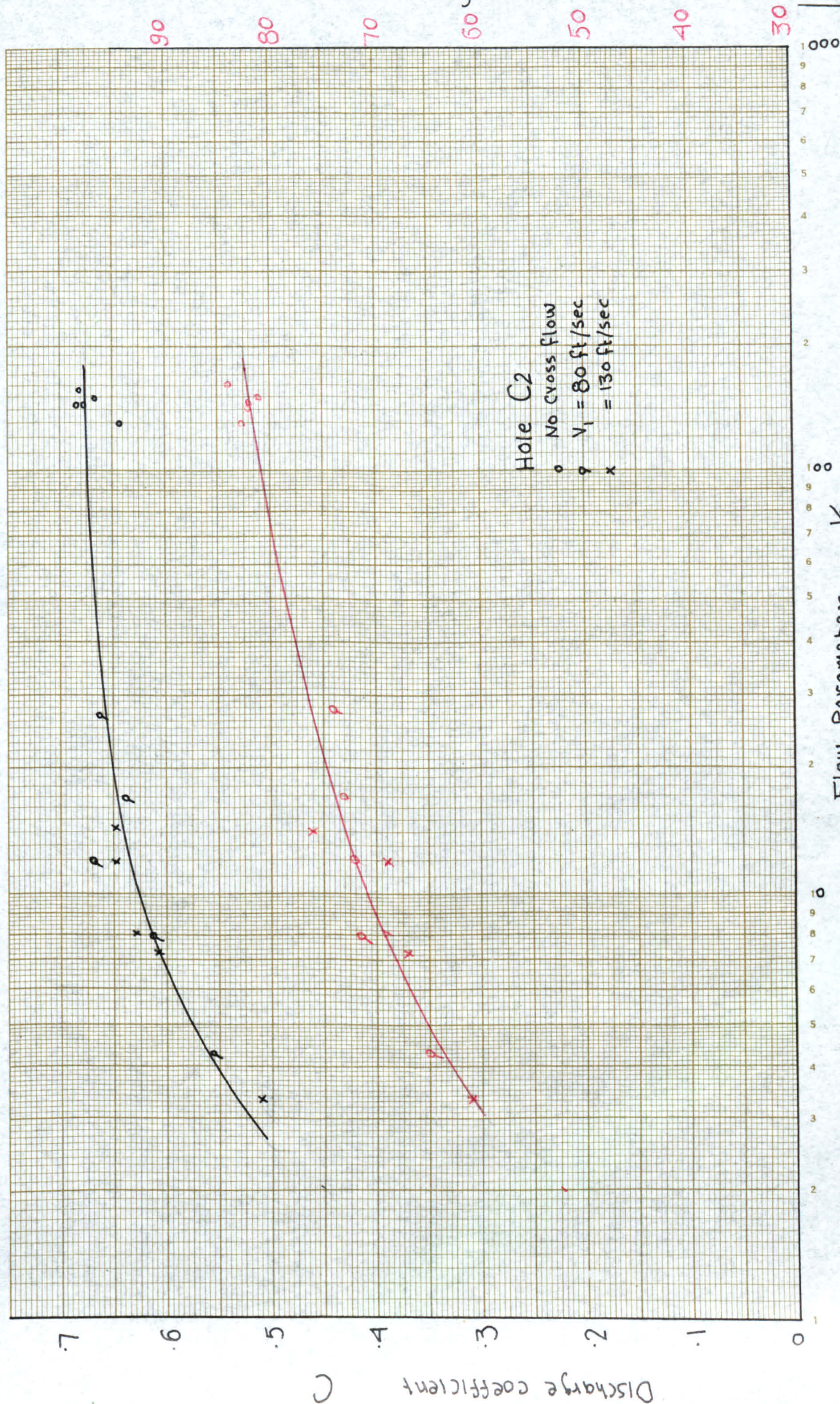


Discharge coefficient and jet deflection for circular holes. $D=0.328$ in., $a^*=0.0595$

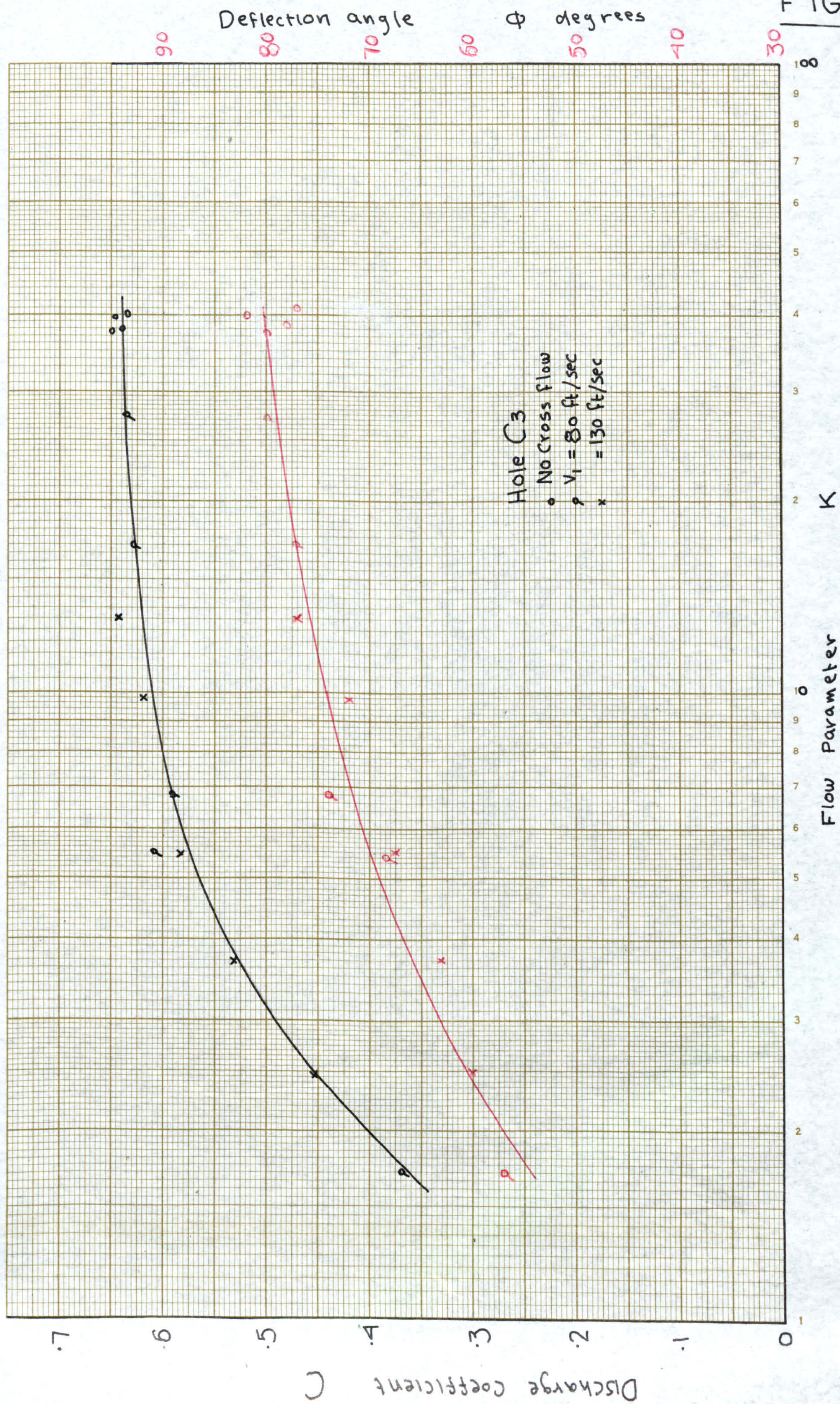
Deflection angle

ϕ degrees

F 16.43



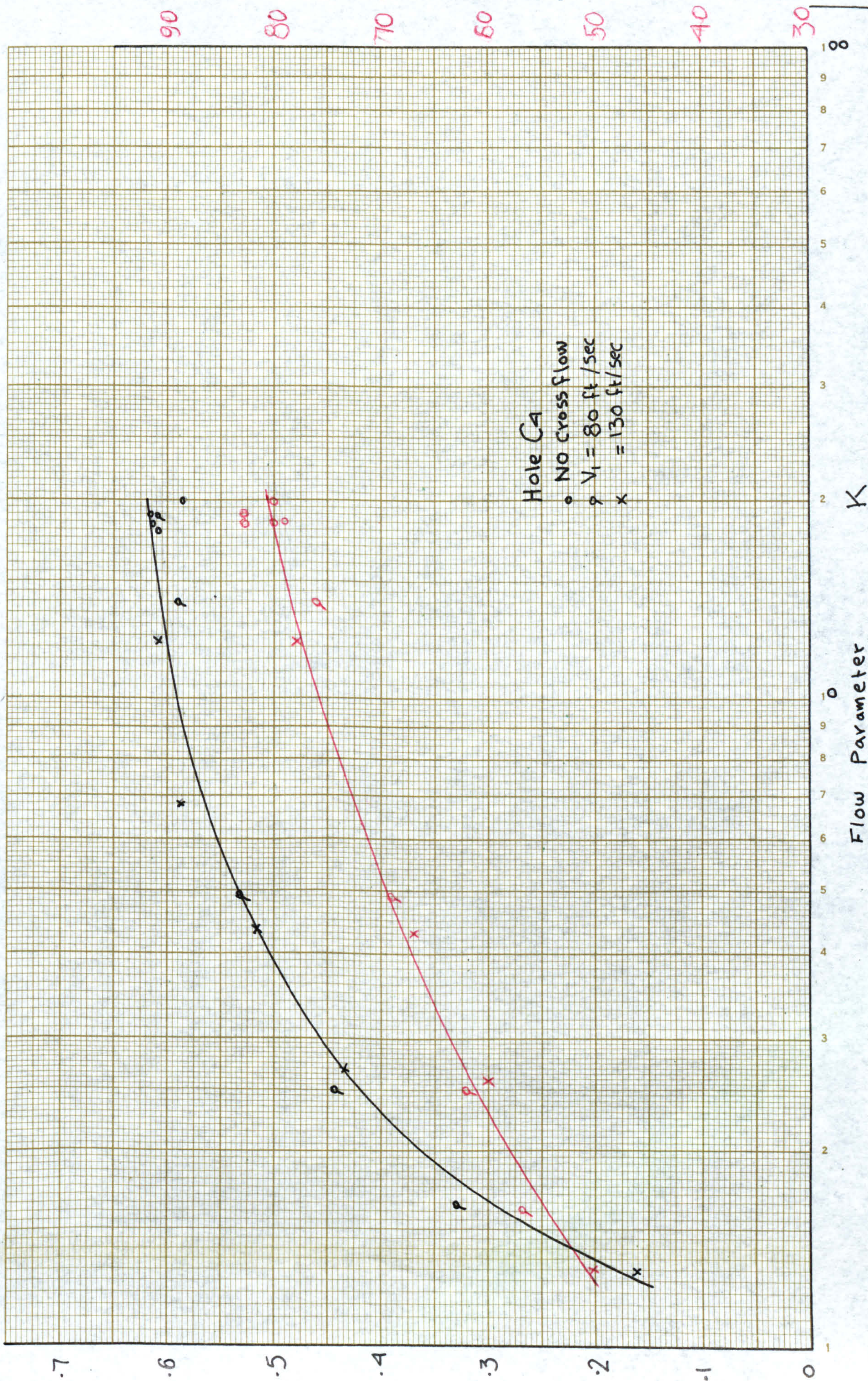
Discharge coefficient and jet deflection for circular holes. $D=0.472 \text{ in.}$, $a=0.1223$



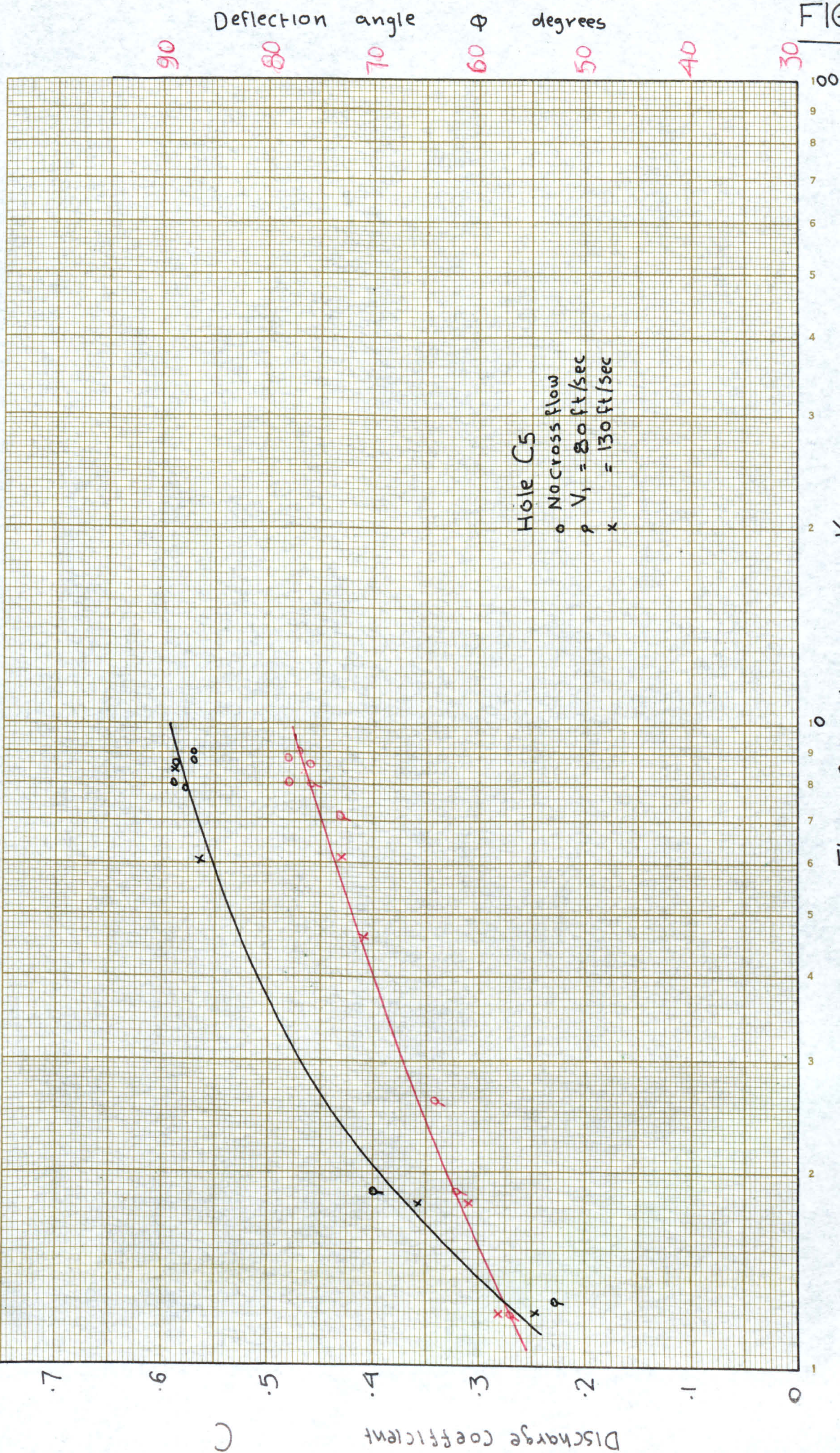
Discharge coefficient and jet deflection for circular holes. $D=0.807 \text{ in.}$ $a=0.2542$

Deflection angle ϕ degrees

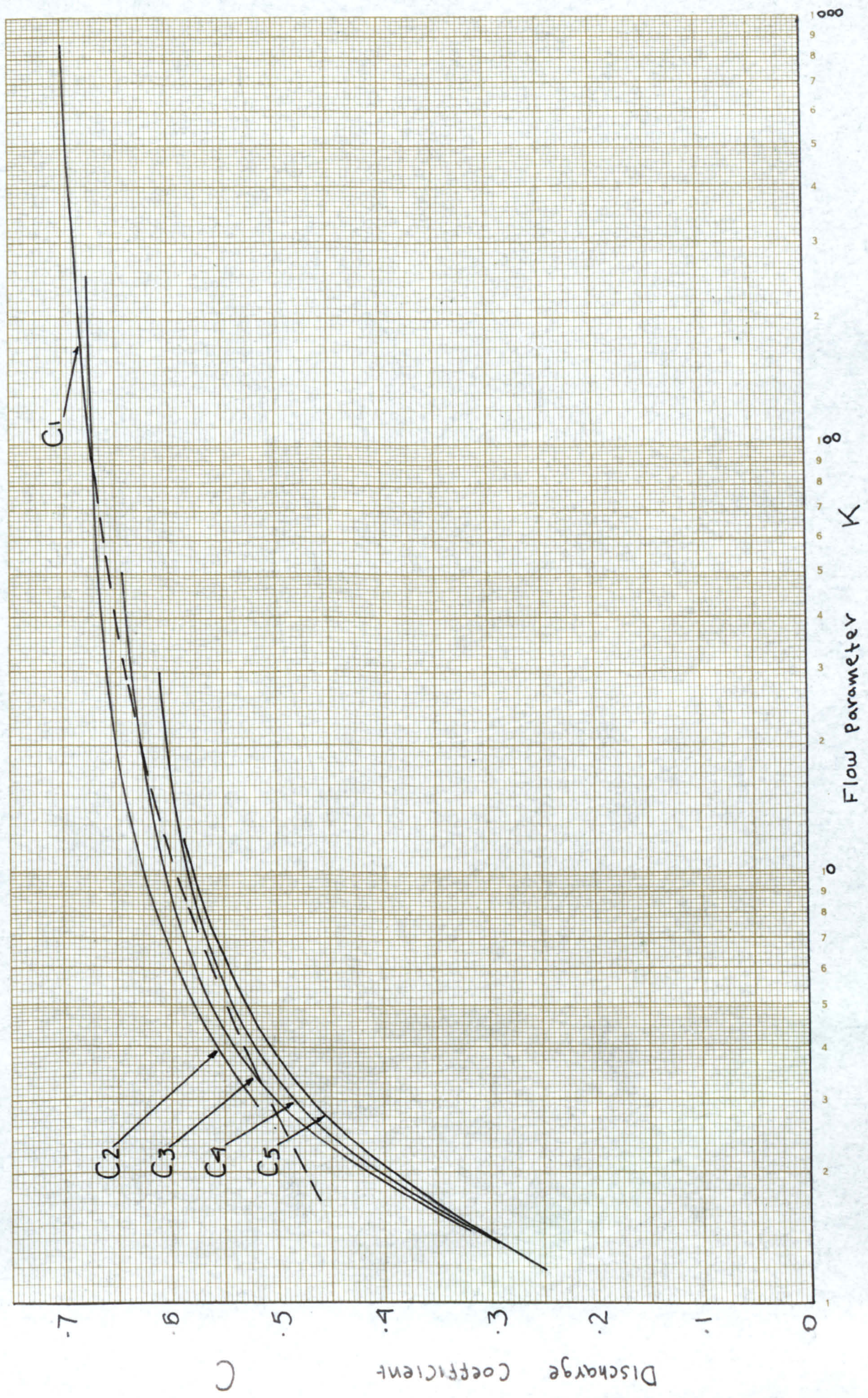
FIG. 45



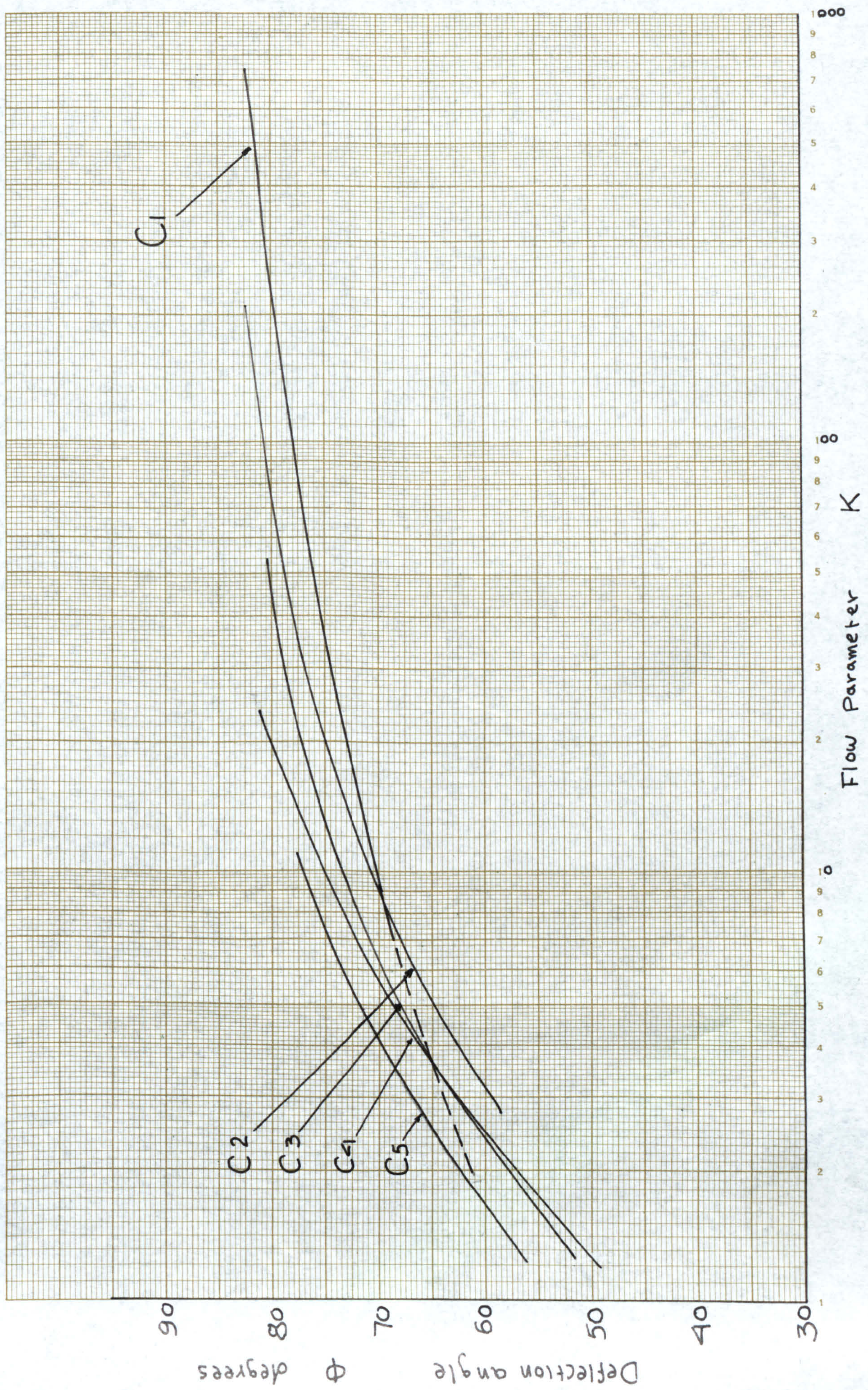
Discharge coefficient and jet deflection for circular holes. $D=0.985 \text{ in.}$, $a=0.3810$



Discharge coefficient and jet deflection for circular holes. $D=1.590 \text{ in.}$, $a=0.595$



Discharge coefficient for circular holes .



Jet deflection for circular holes •

FIG. 49

Discharge coefficient and
jet deflection for Oval
slots.

$b = a = .2180"$, $a^* = .0595$

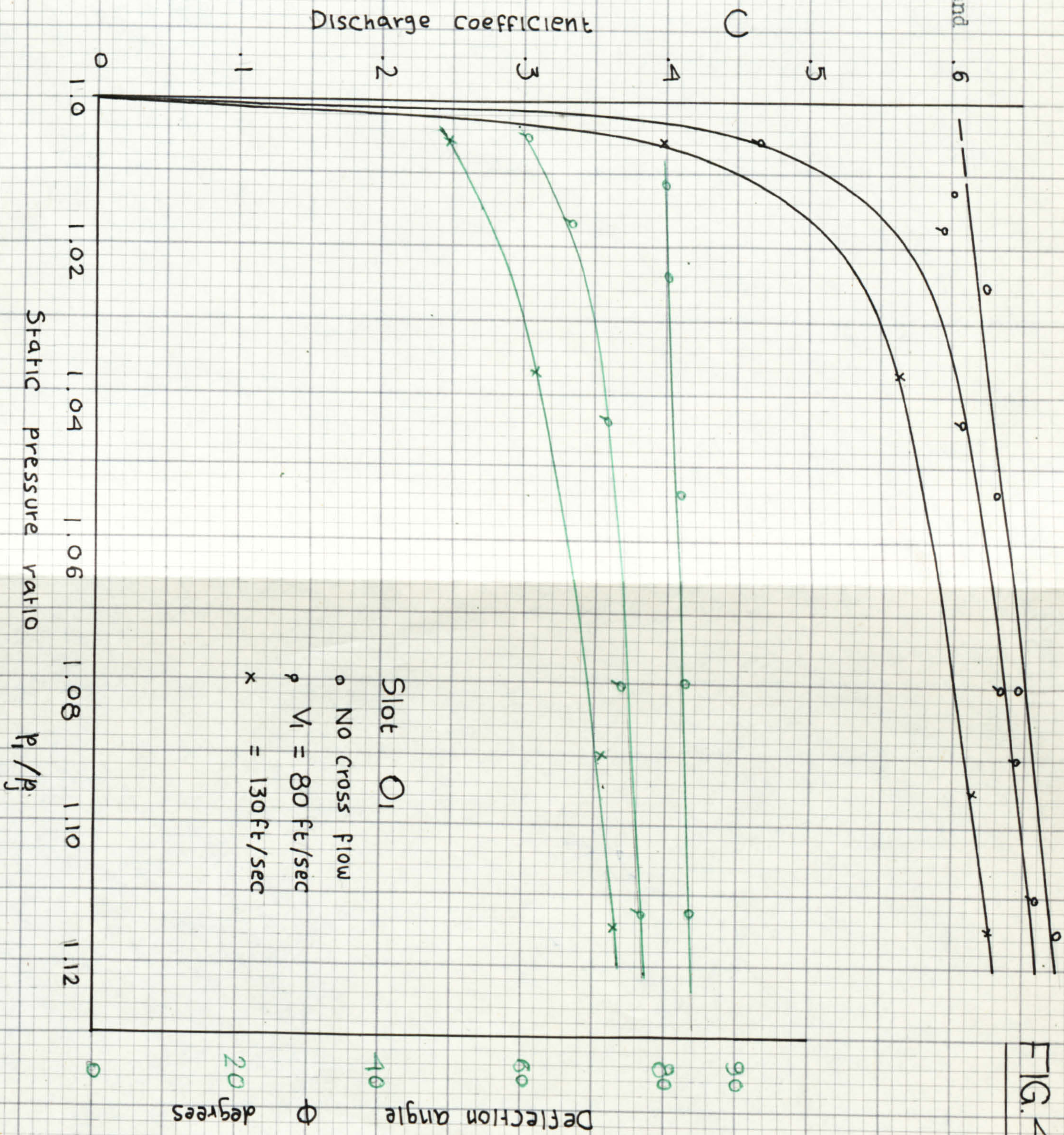
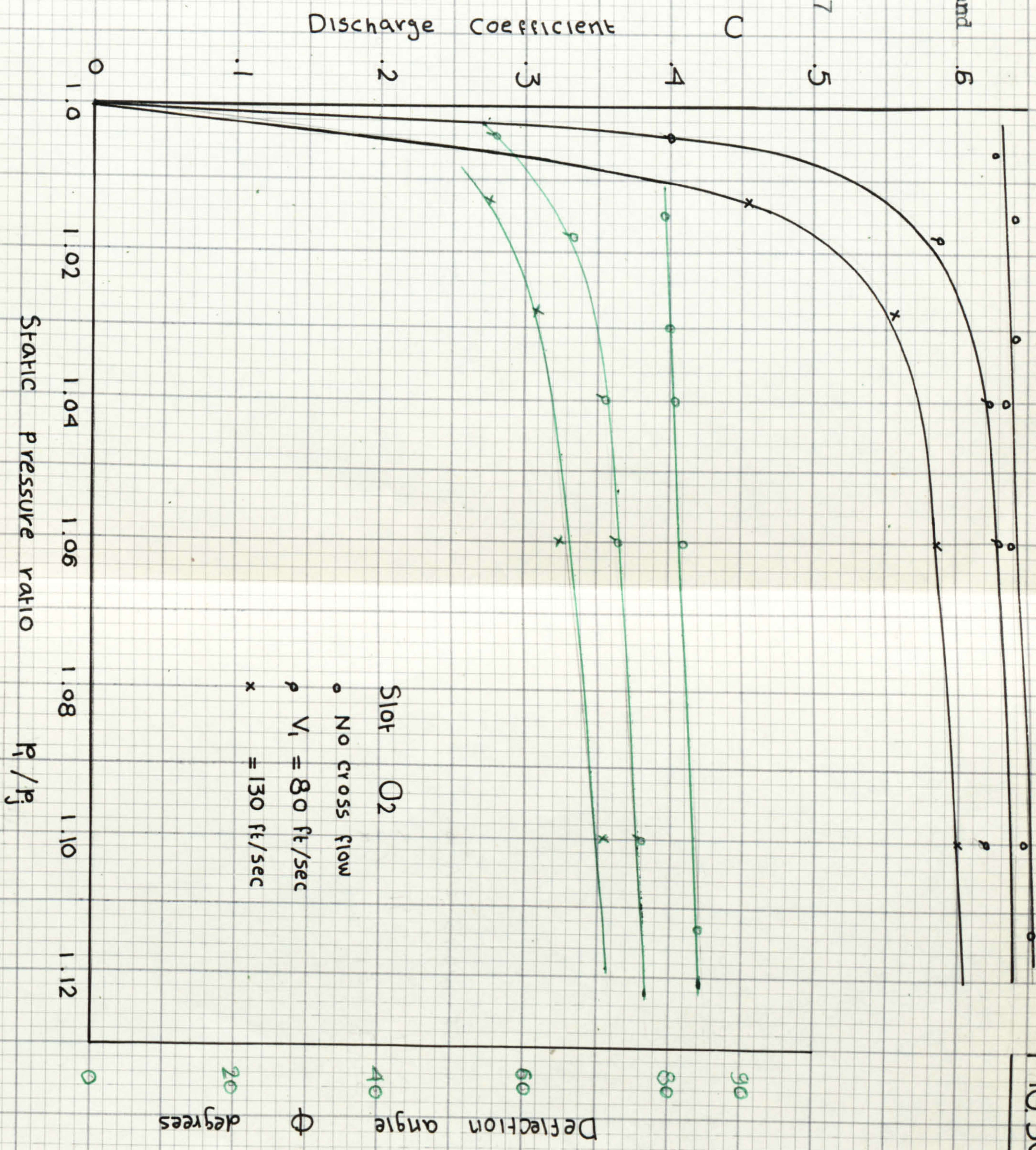


FIG. 50

Discharge coefficient and
jet deflection for Oval
slots •

$a=b = .3120 \text{ in.}, a^* = .1217$



Discharge coefficient and
jet deflection for Oval
slots .

$a=b=.5310 \text{ in.}$, $a^*=.2520$

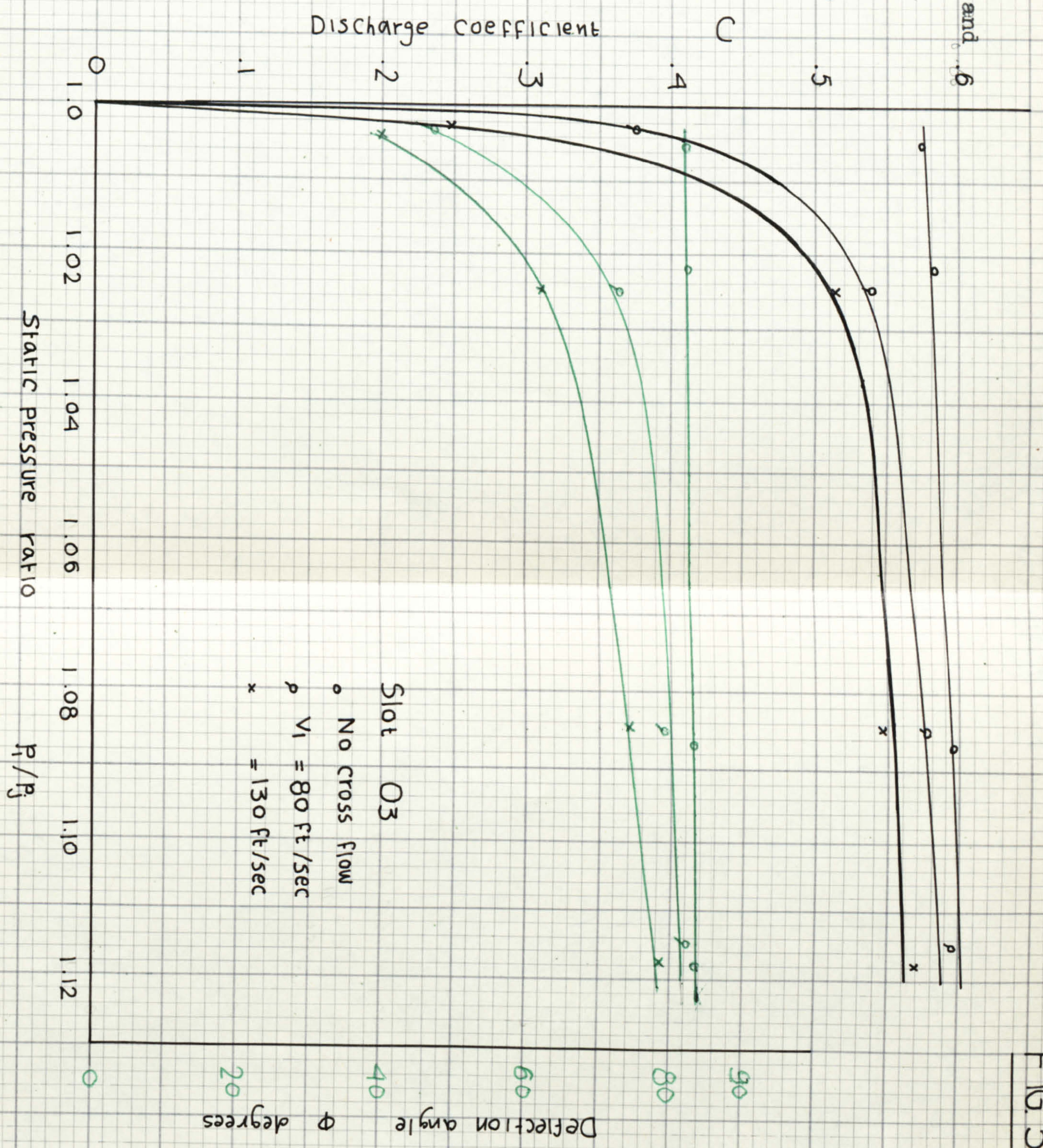


FIG. 52

Discharge coefficient and
jet deflection for Oval
slots .

$a=b=.6560 \text{ in.}$, $a^*=.3840$

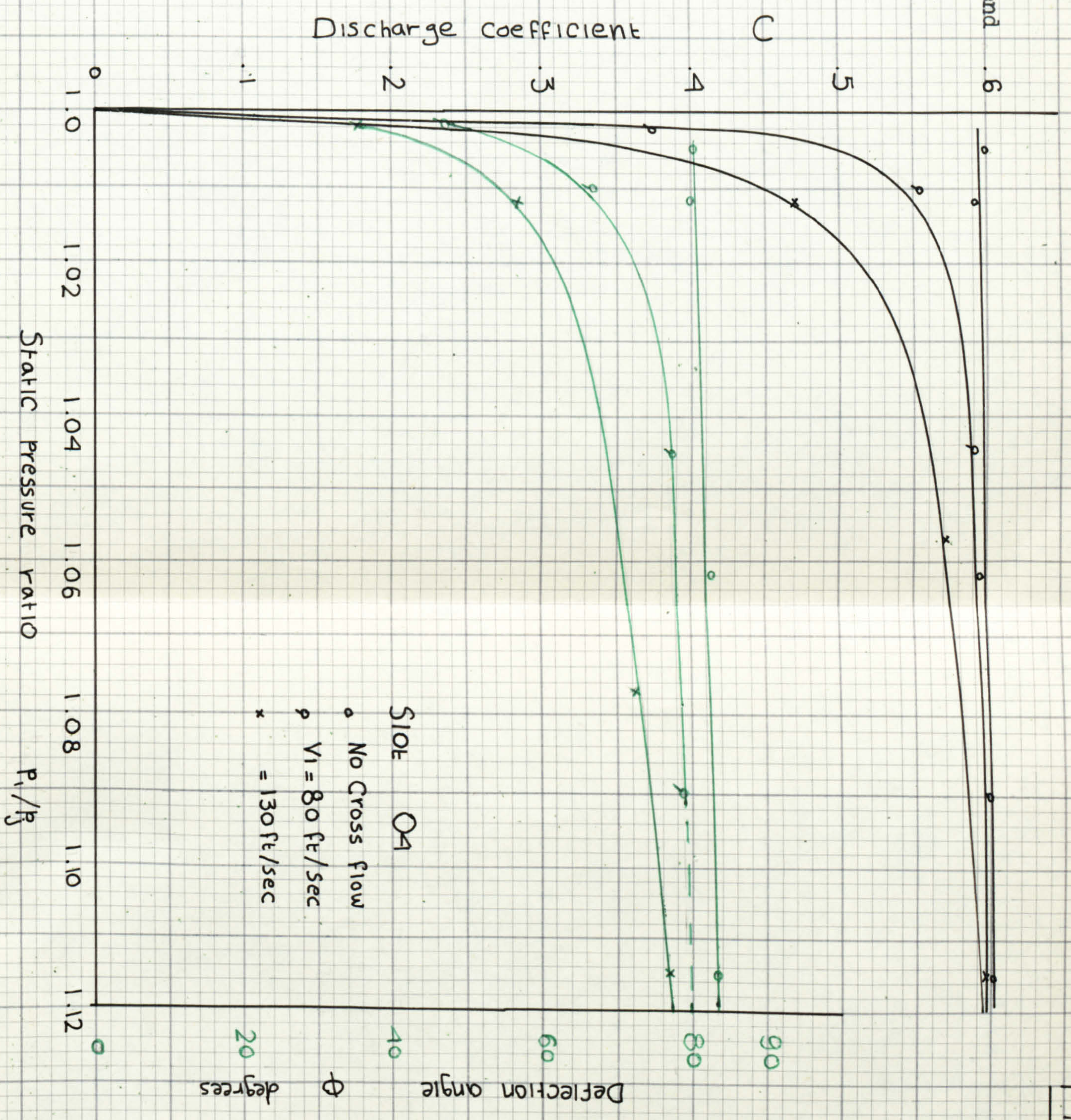
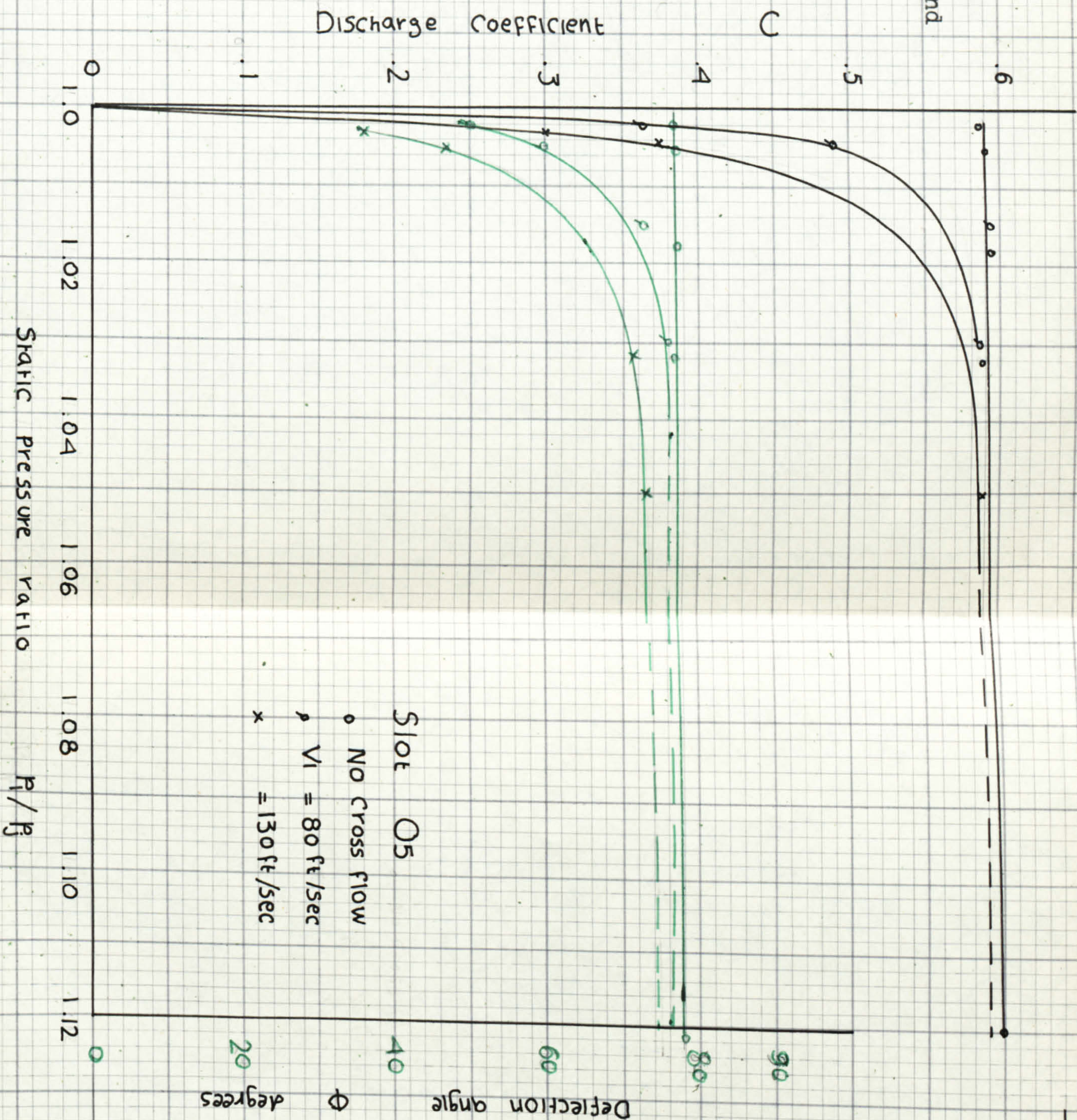


FIG. 53

Discharge coefficient and
jet deflection for Oval

slots .

$a=b=1.062$ in. , $a^*=.6040$

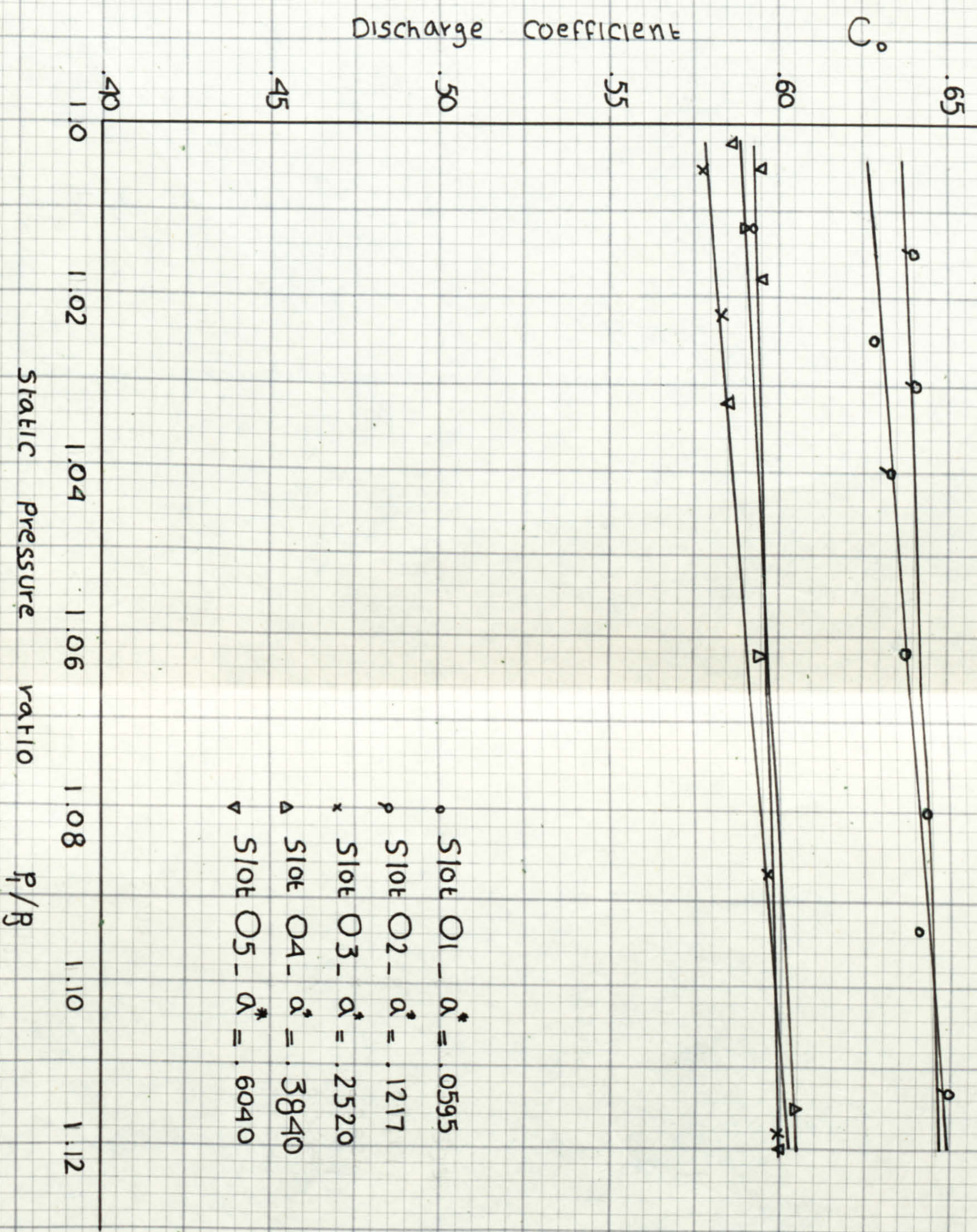


Discharge coefficient

for Oval slots ,

Aspect ratio = 2.0

No cross flow .

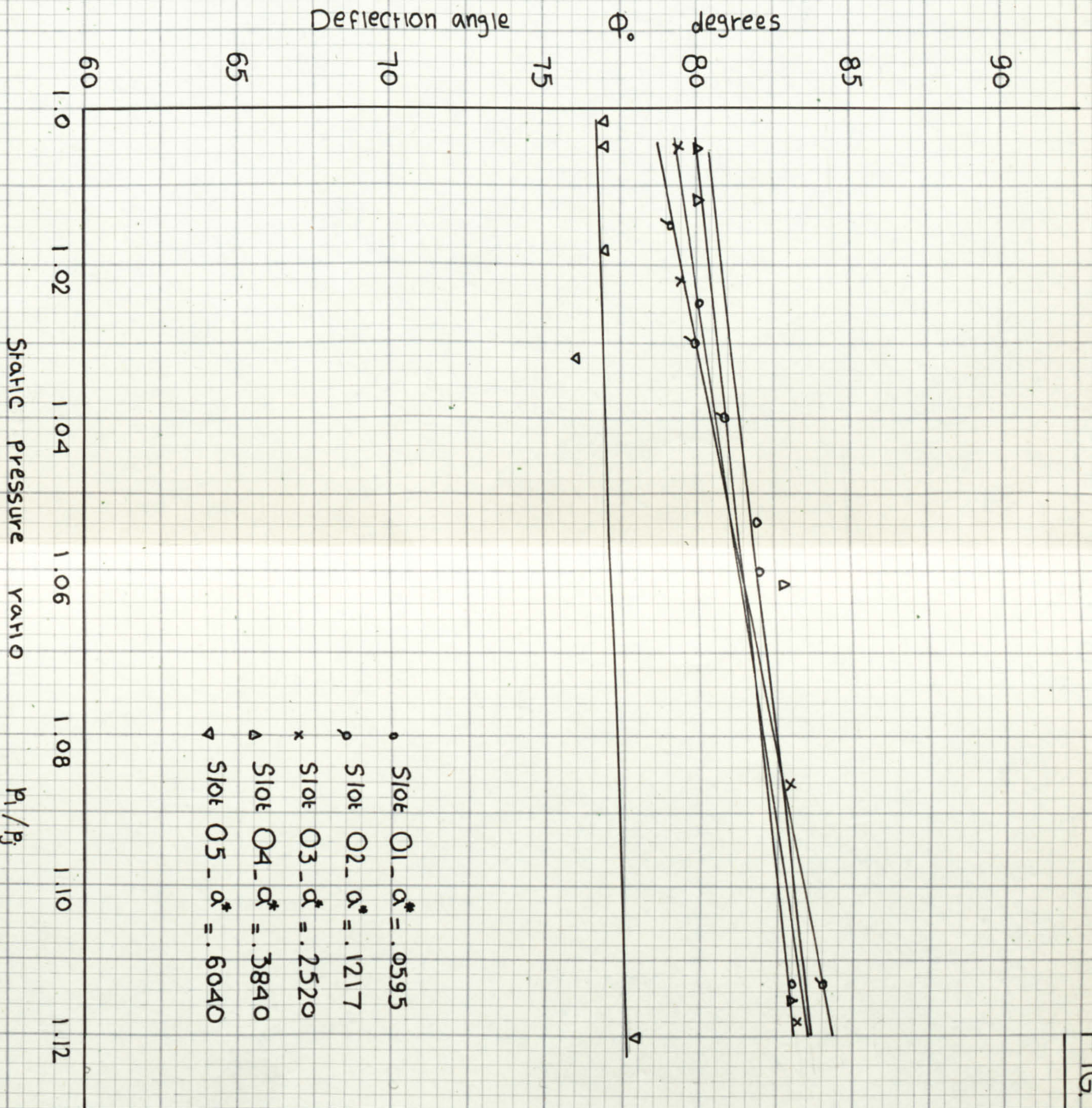


Deflection angle for

Oval slots,

Aspect ratio = 2.0

No cross flow.



Discharge coefficient and
jet deflection for Oval
slots .

$a = .375 \text{ in.}$, $b = 1.122 \text{ in.}$

Area ratio $= .2520$

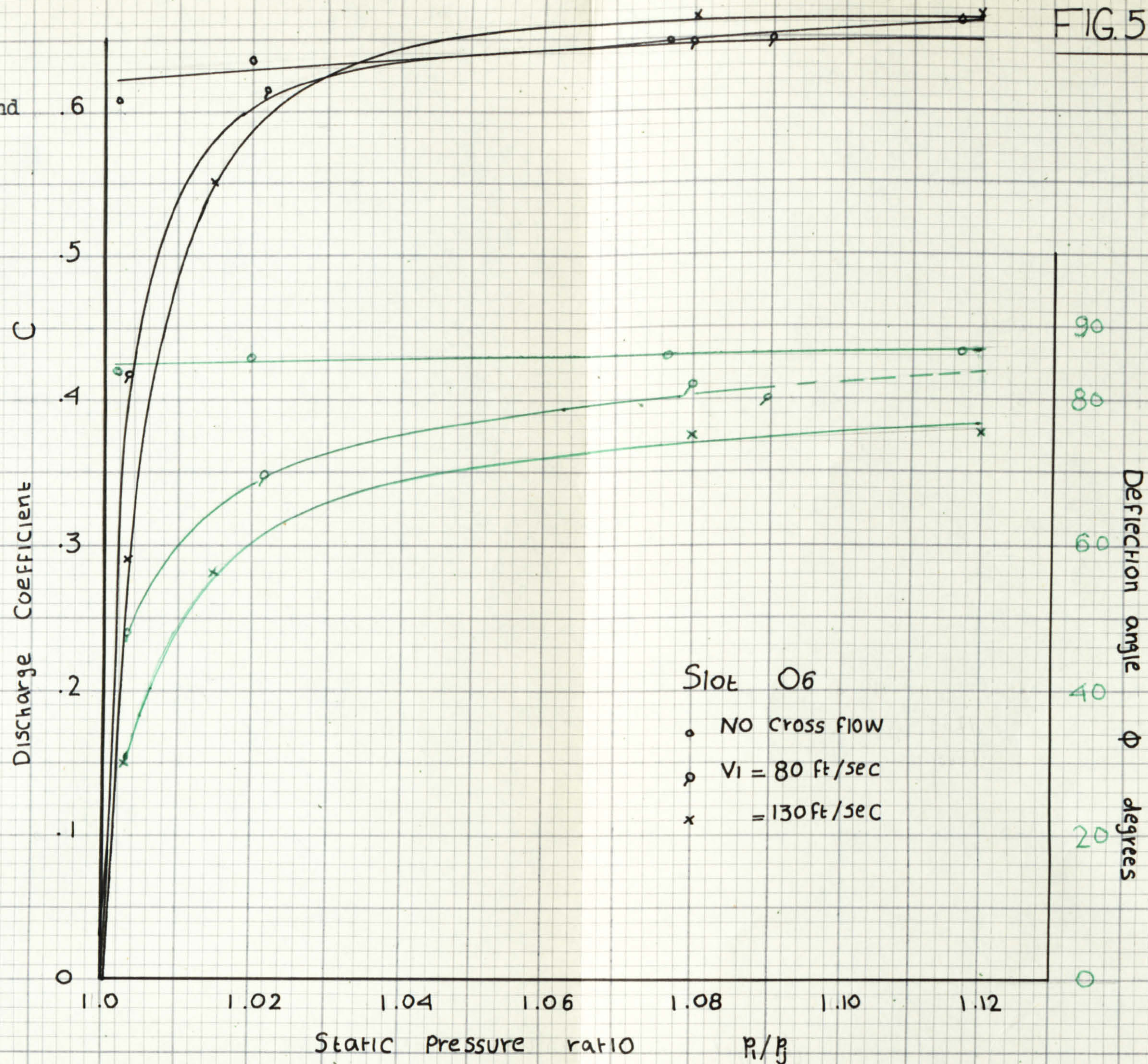
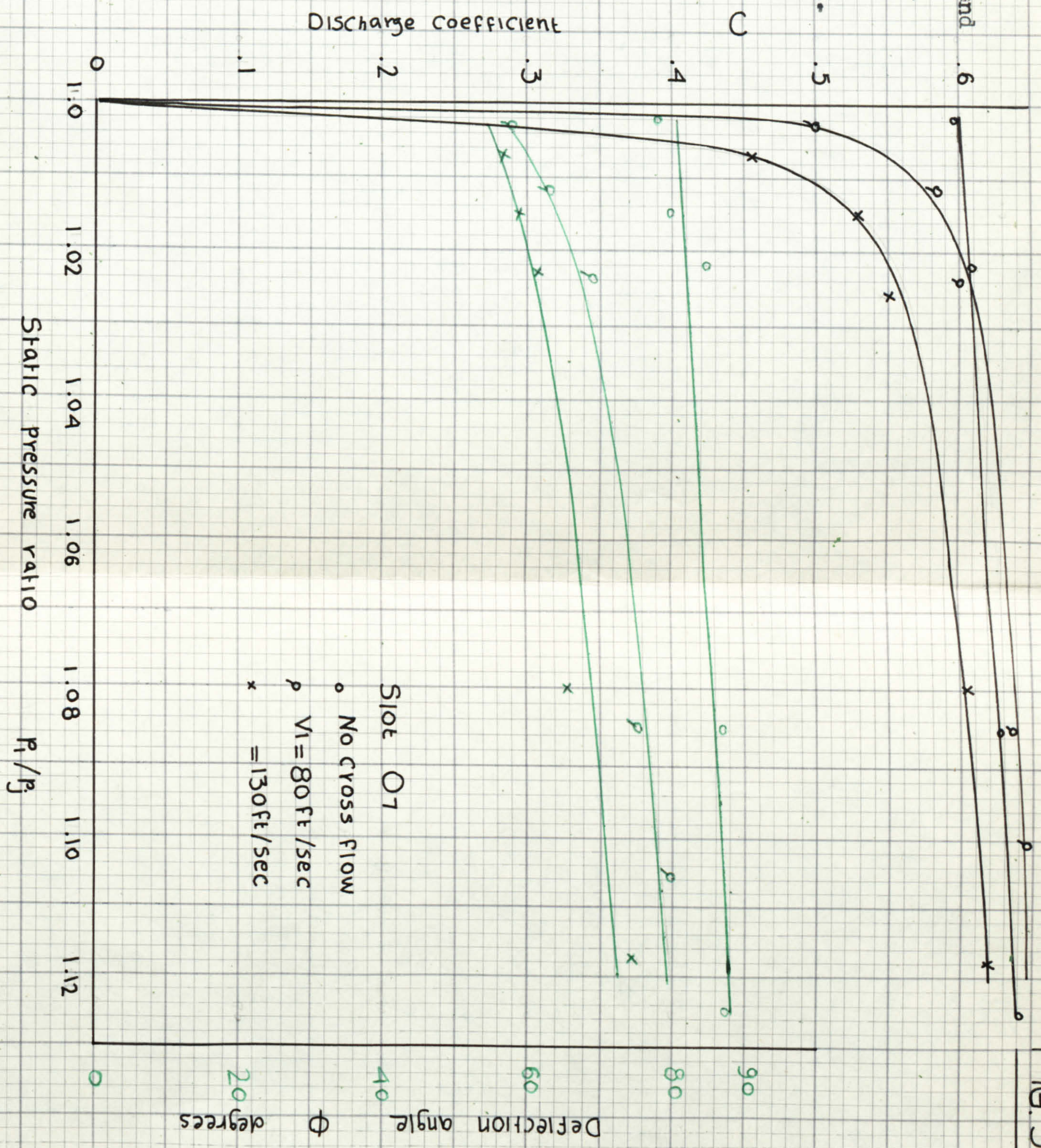


FIG. 57

Discharge coefficient and
jet deflection for Oval
slots.

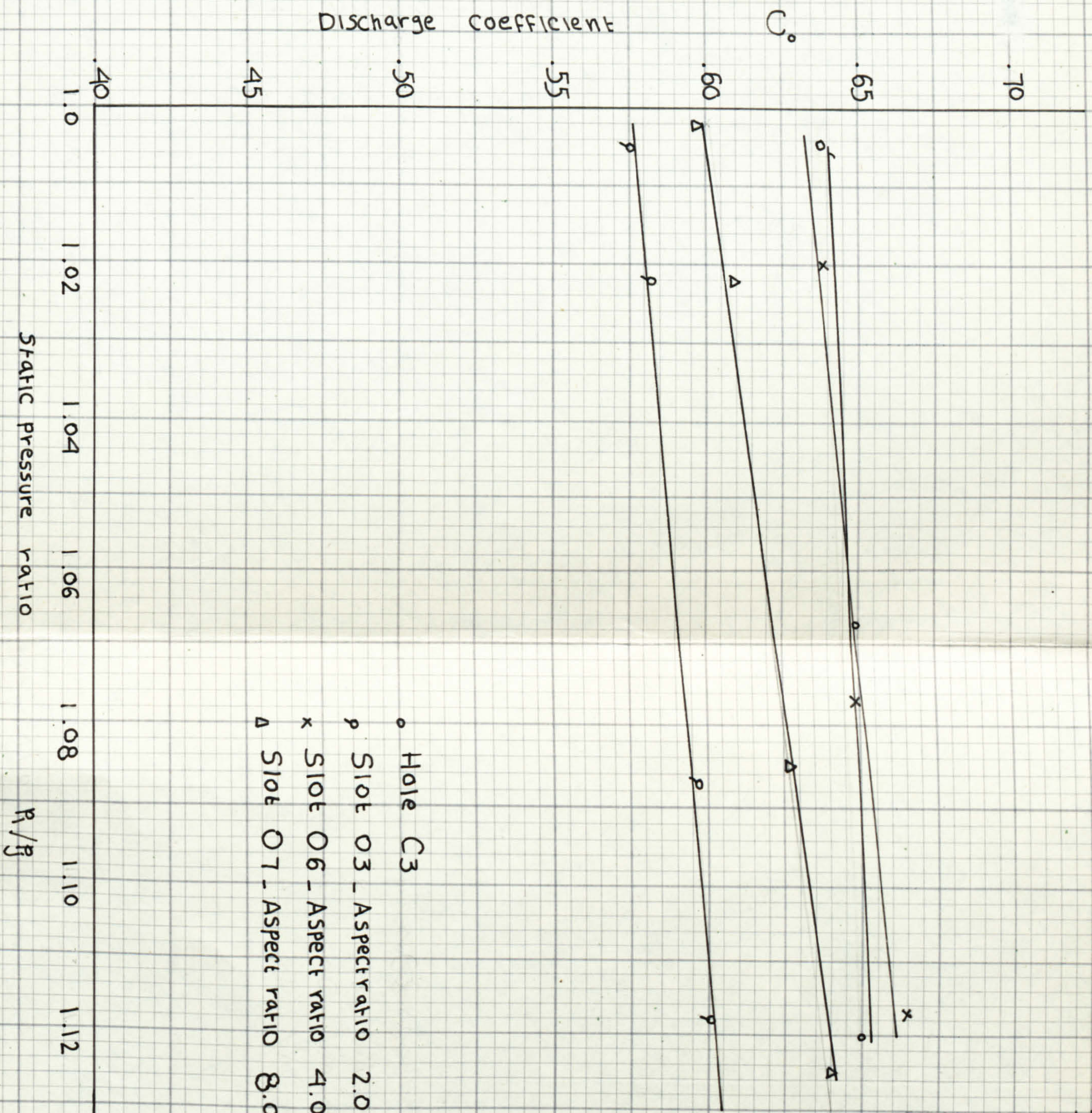
$a = .250$ in., $b = 1.850$ in.
Area ratio = .2520



Discharge coefficient
for Oval slots .

Area ratio = .2520

No cross flow .

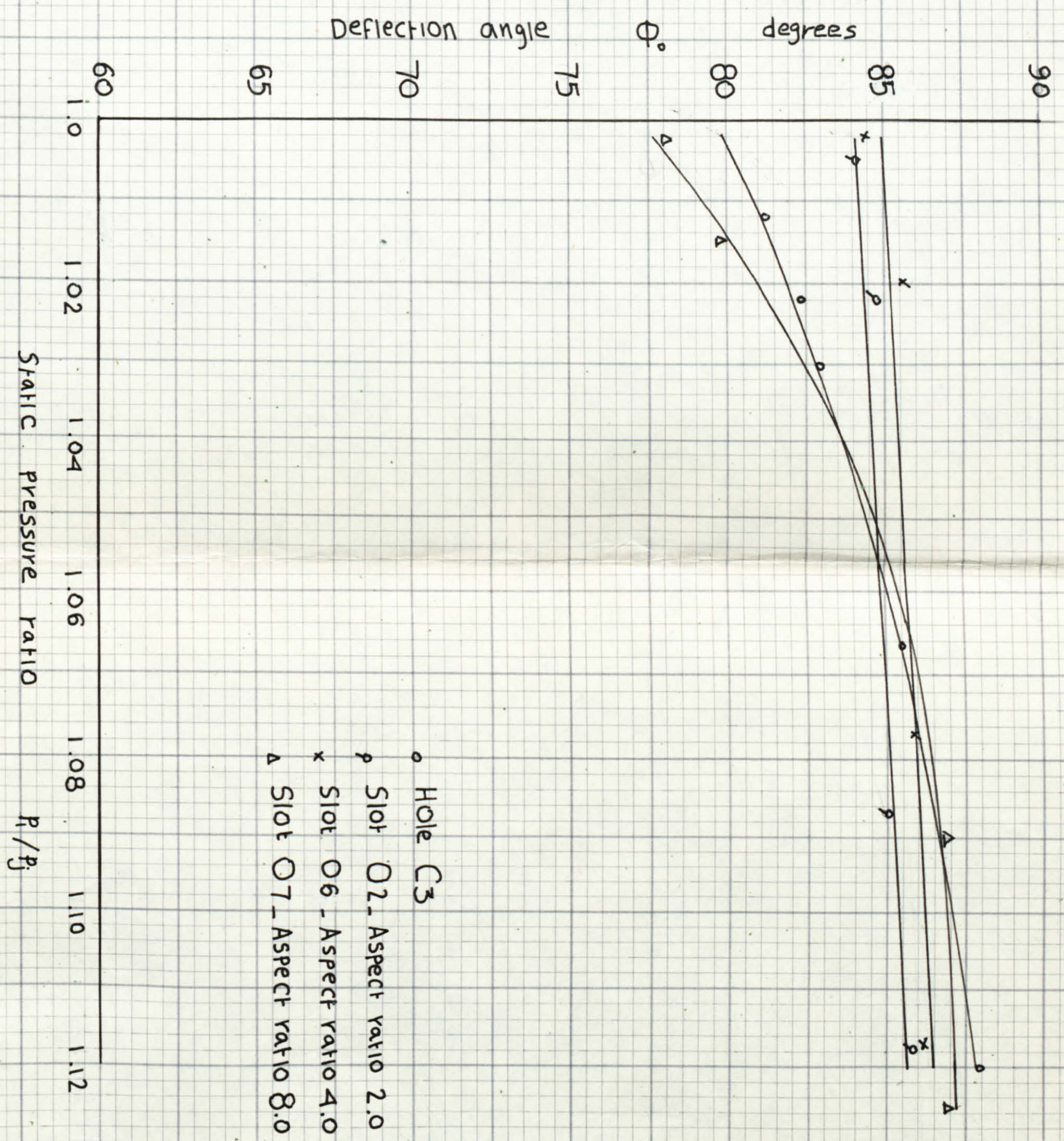


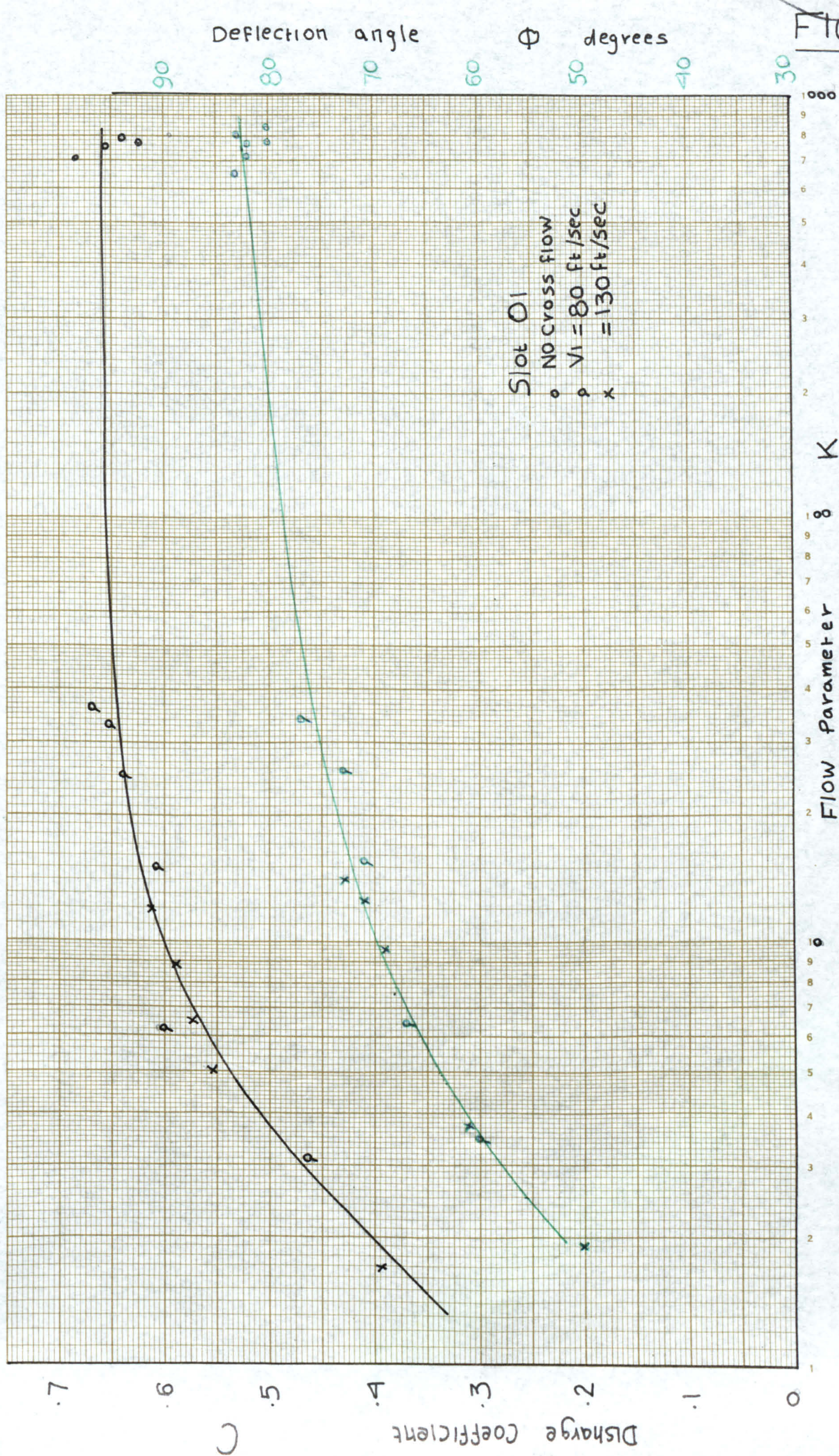
Deflection angle for

Oval slots .

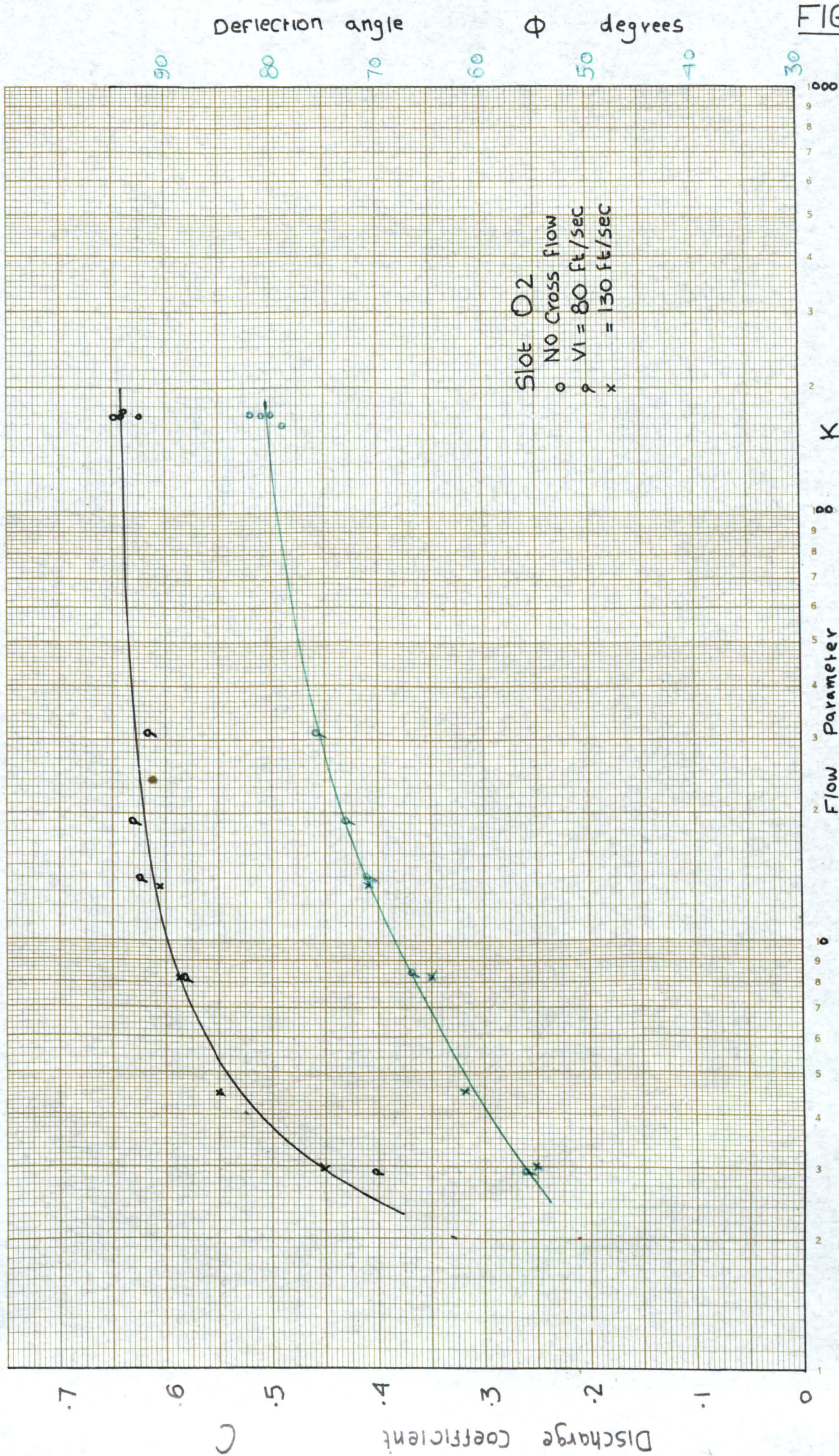
Area ratio = .2520

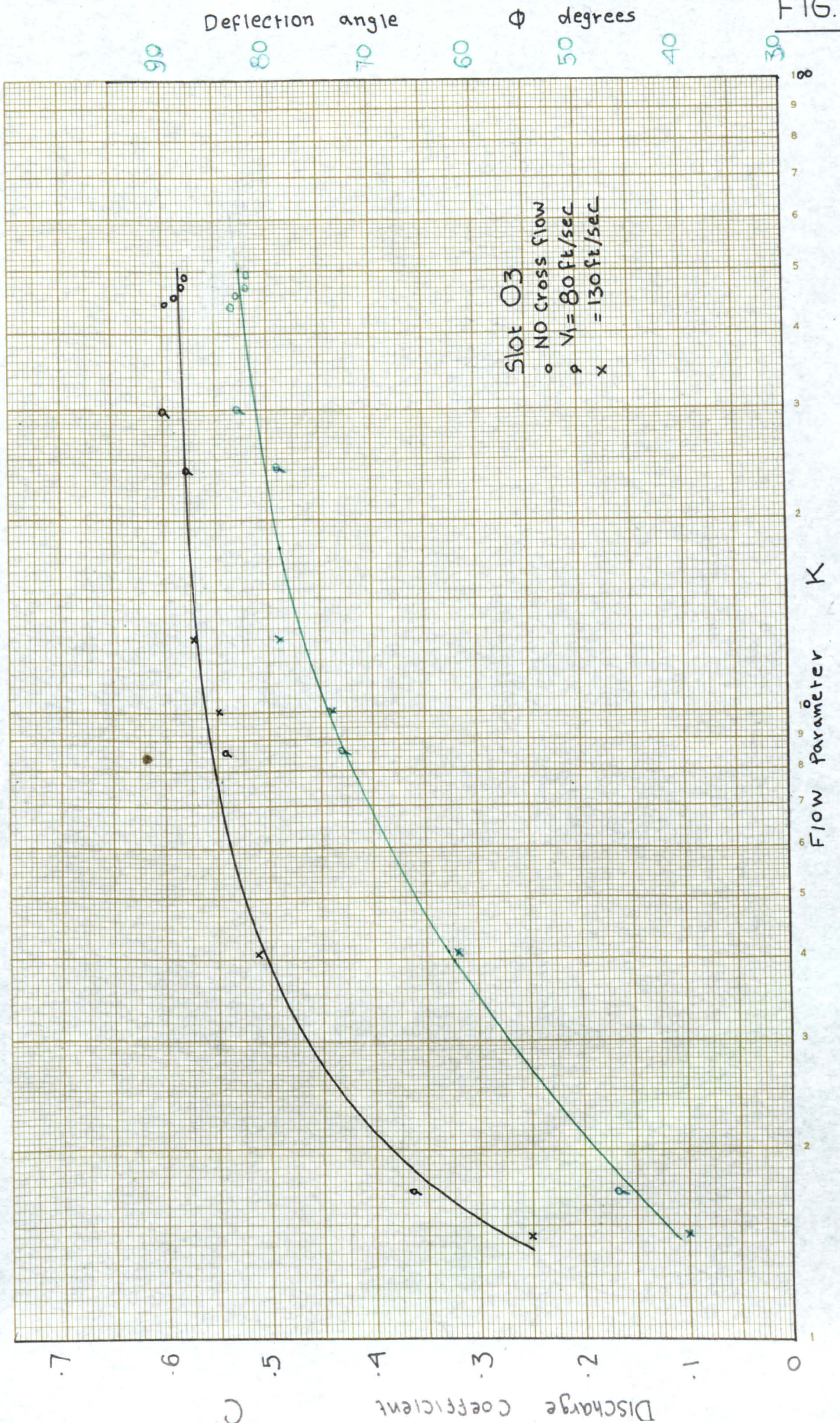
No cross flow .

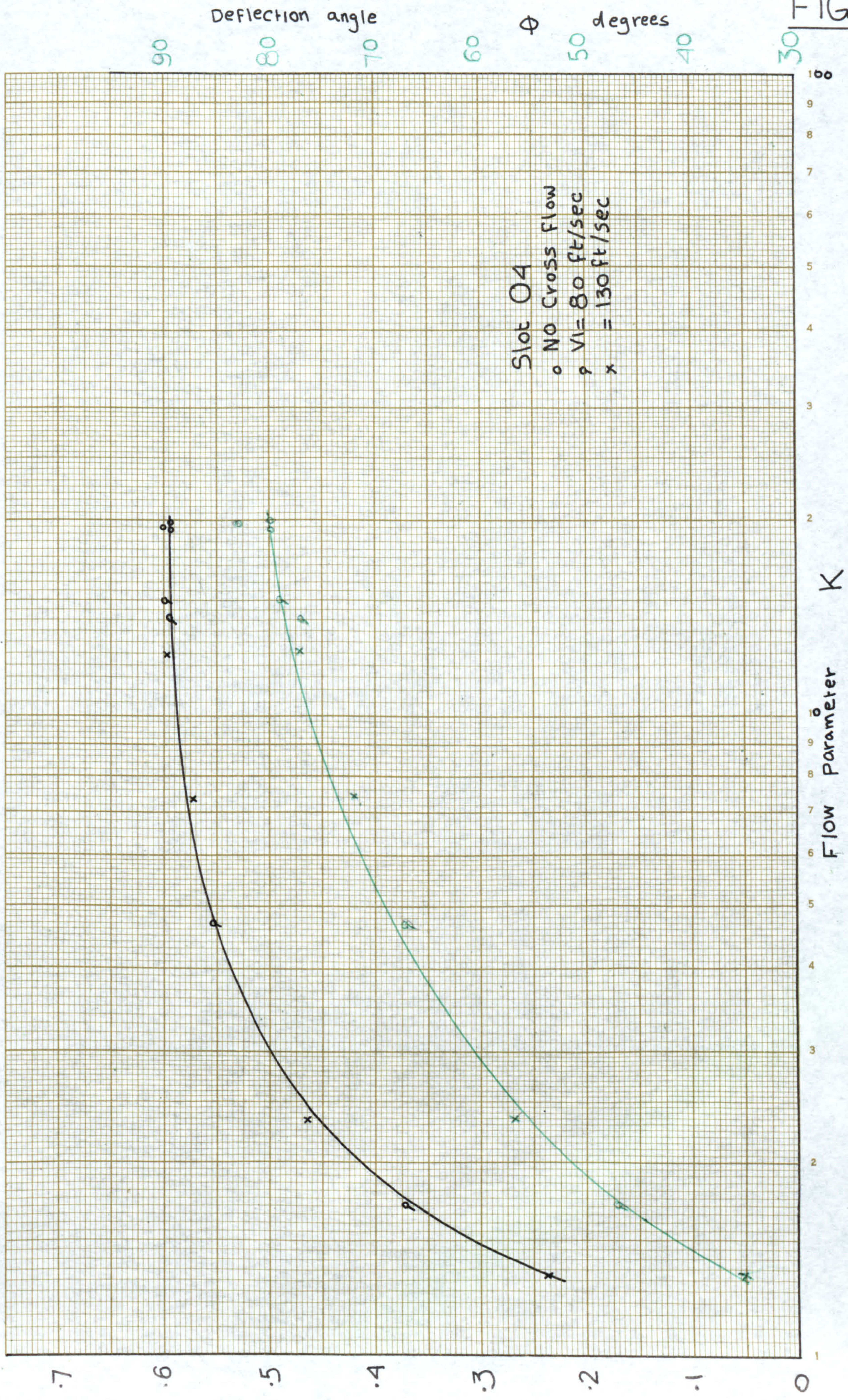




Discharge coefficient and jet deflection for Oval slots. ($a=b=0.218 \text{ in.}$, $a^* = 0.0595$)



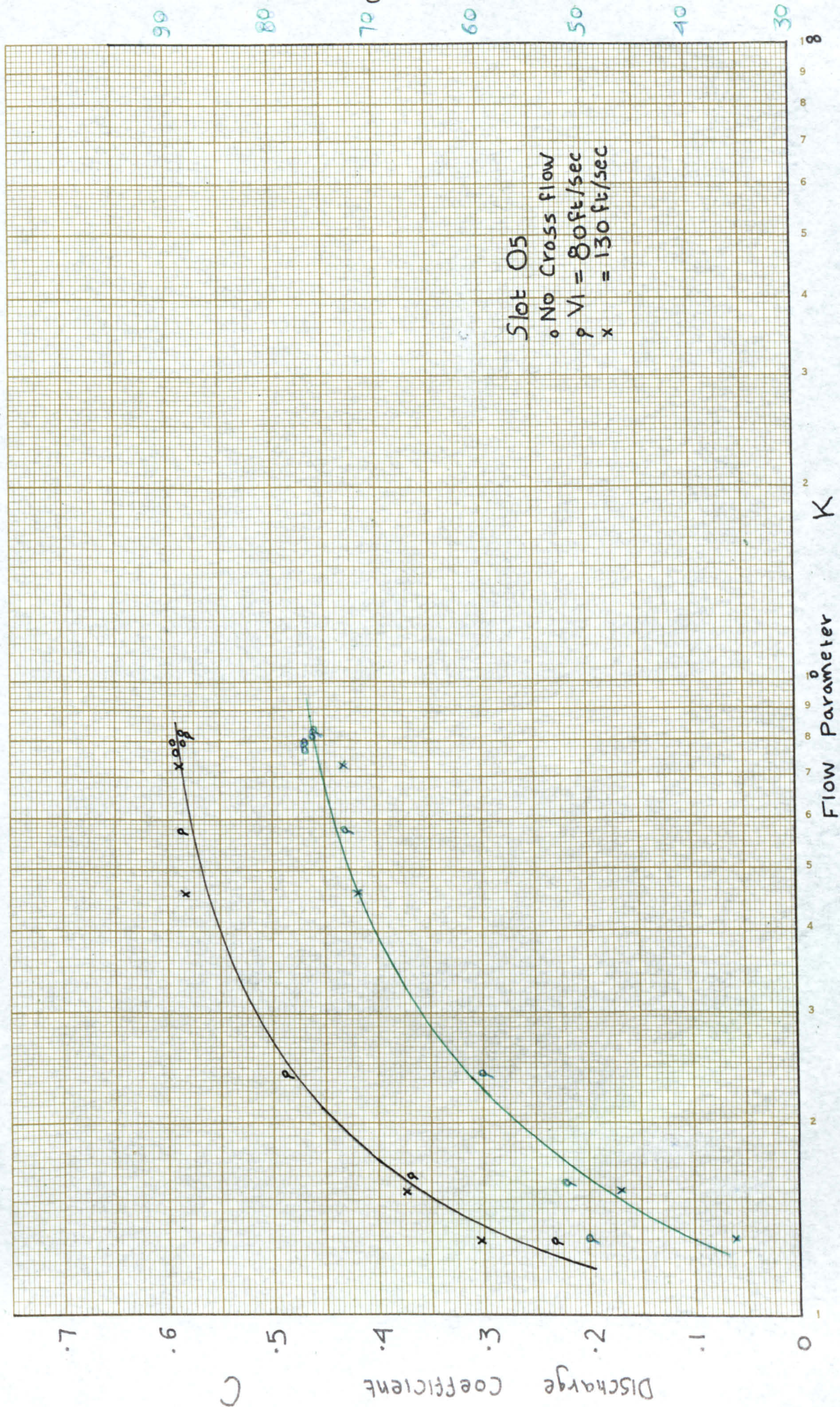




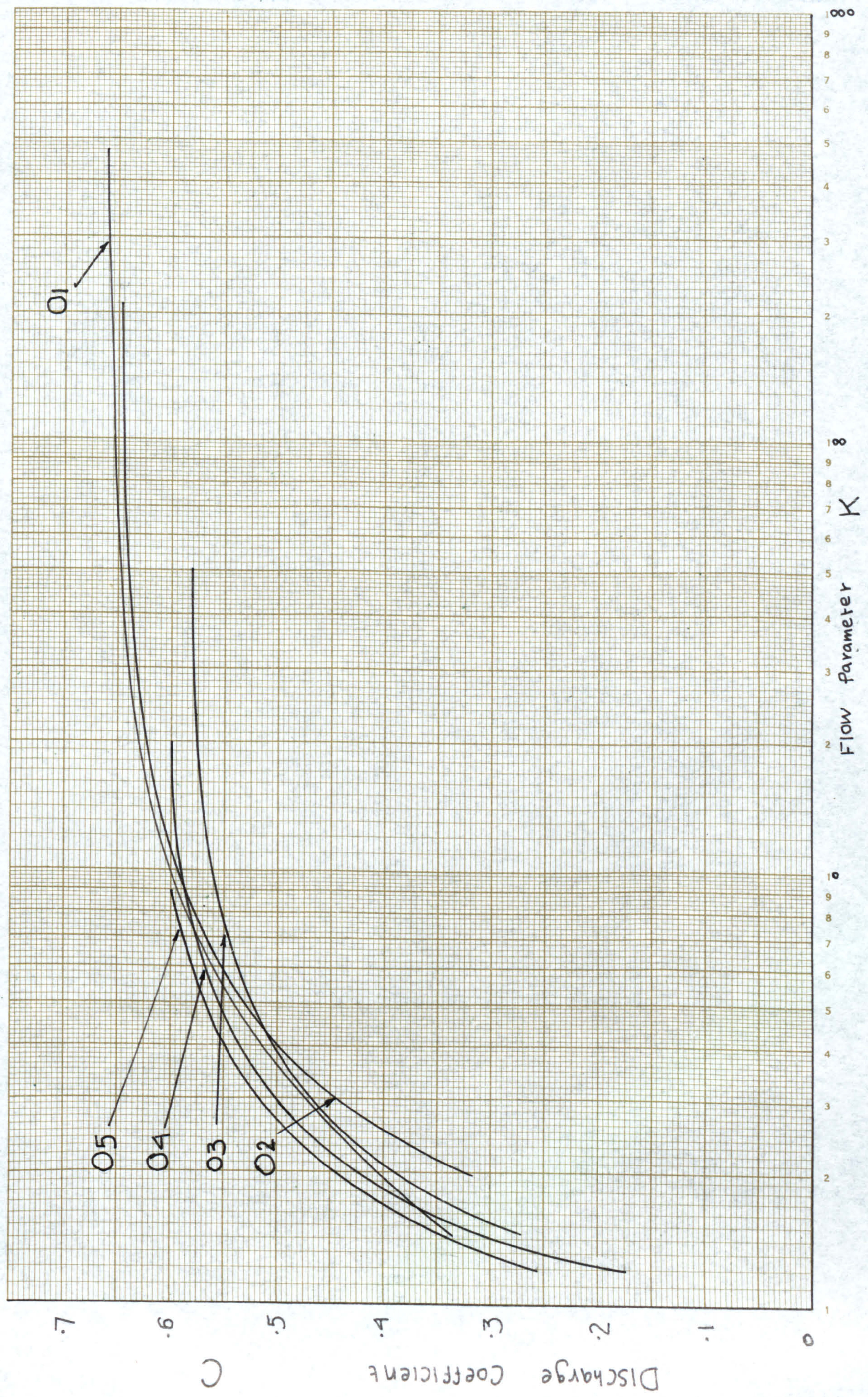
Discharge coefficient and jet deflection for Oval slots. ($a=b=.656$ in., $a^*=.3840$)

Deflection angle ϕ degrees

FIG. 64

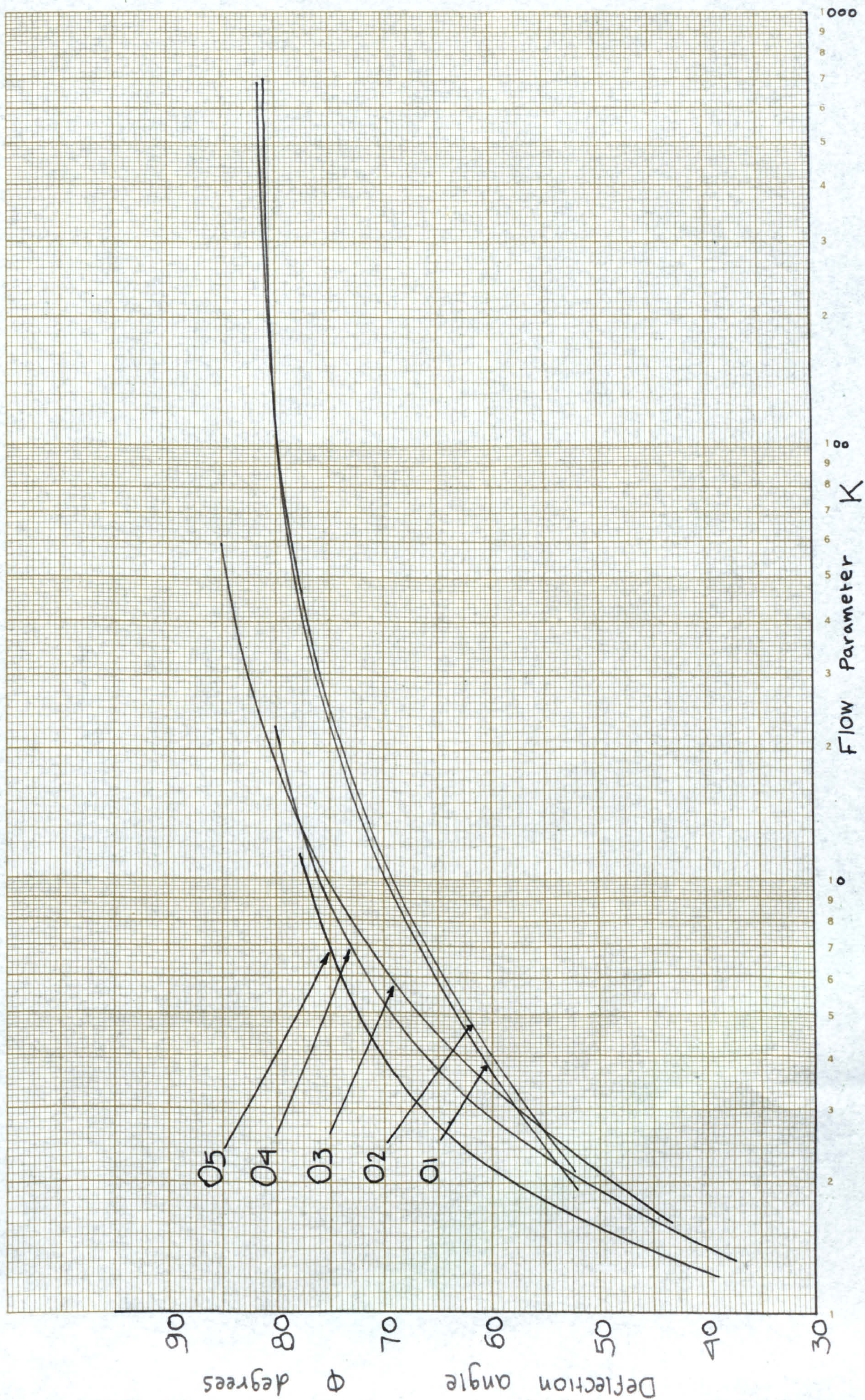


Discharge coefficient C_d and jet deflection for Oval slots. ($a=b=1.062 \text{ in.}$, $a^*=0.6040$)



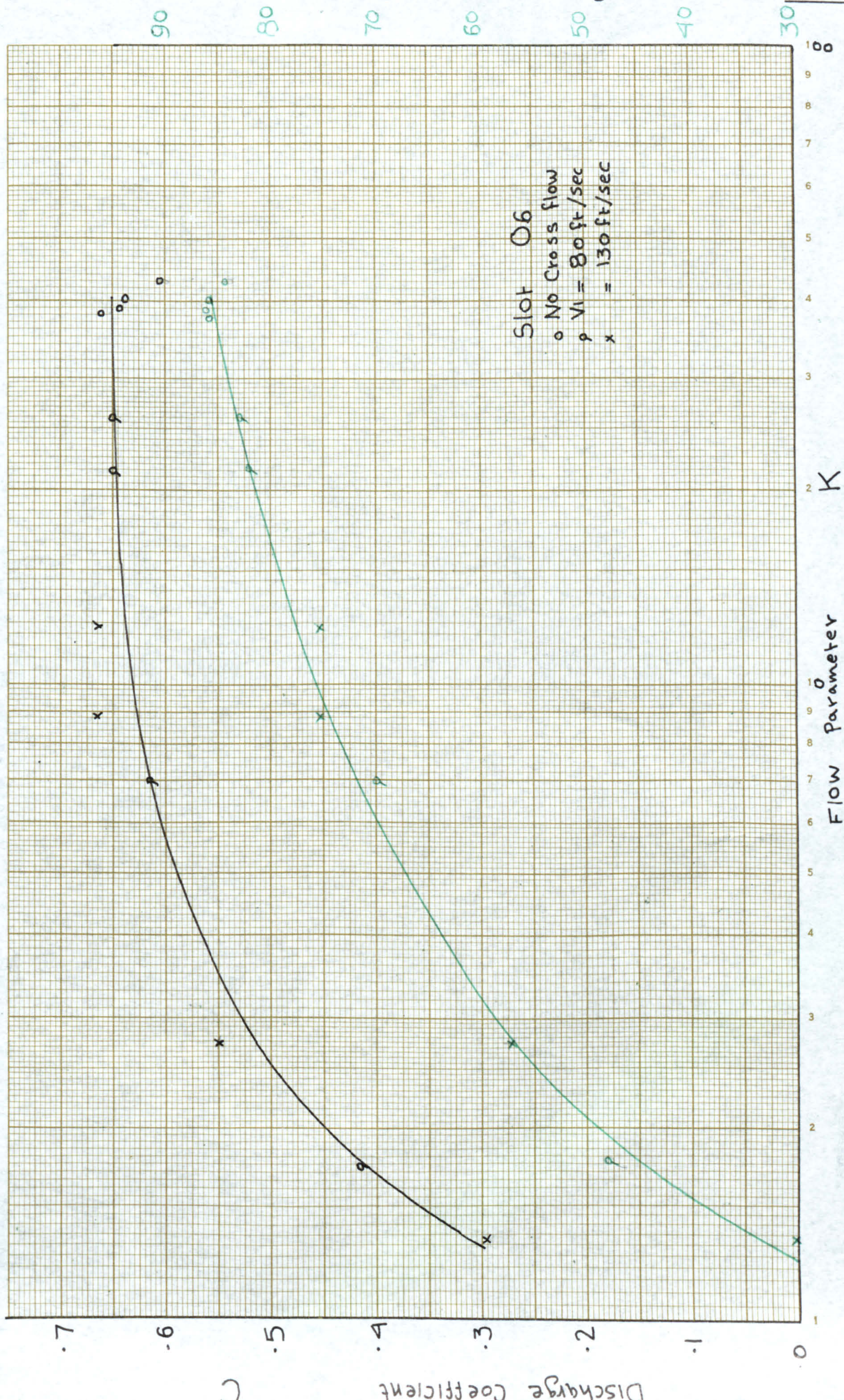
Discharge coefficient for Oval slots • (Aspect ratio = 2.0)

FIG.66



Jet deflection for Oval slots . (Aspect ratio = 2.0)

Deflection angle ϕ degrees

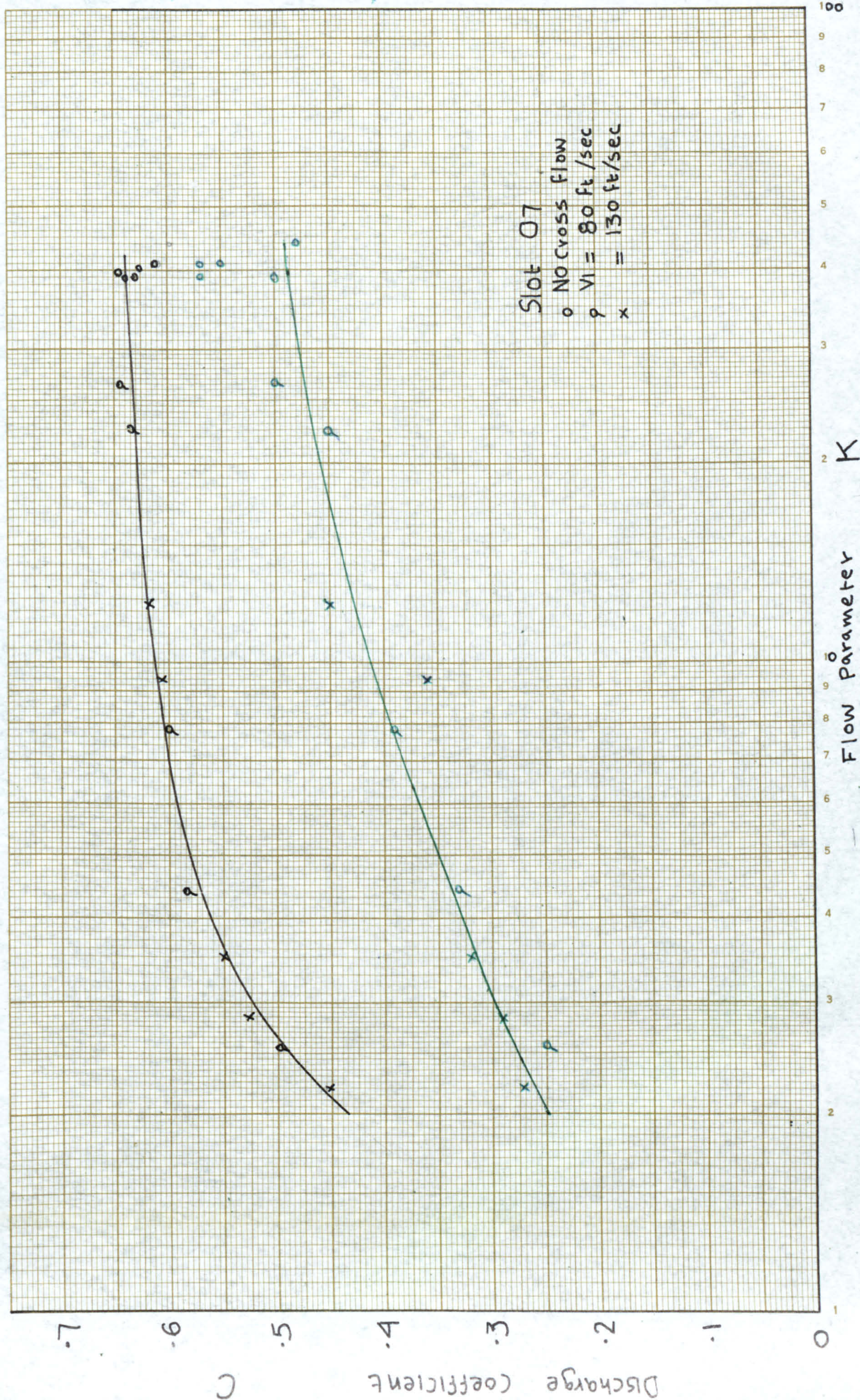


Discharge coefficient and jet deflection for Oval slots. ($a=0.375$, $b=1.122$, $a^*=0.252$)

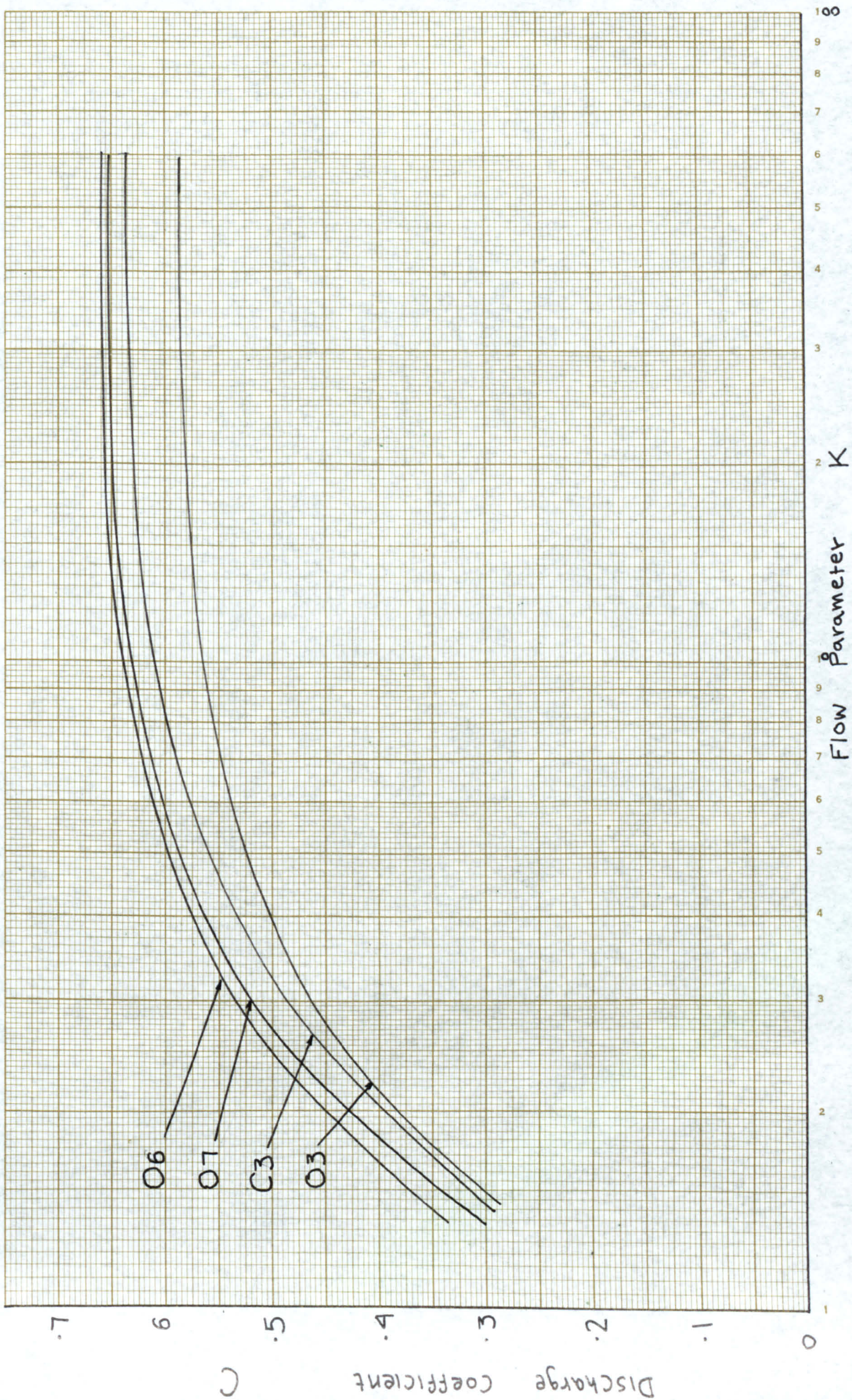
Deflection angle

Φ degrees

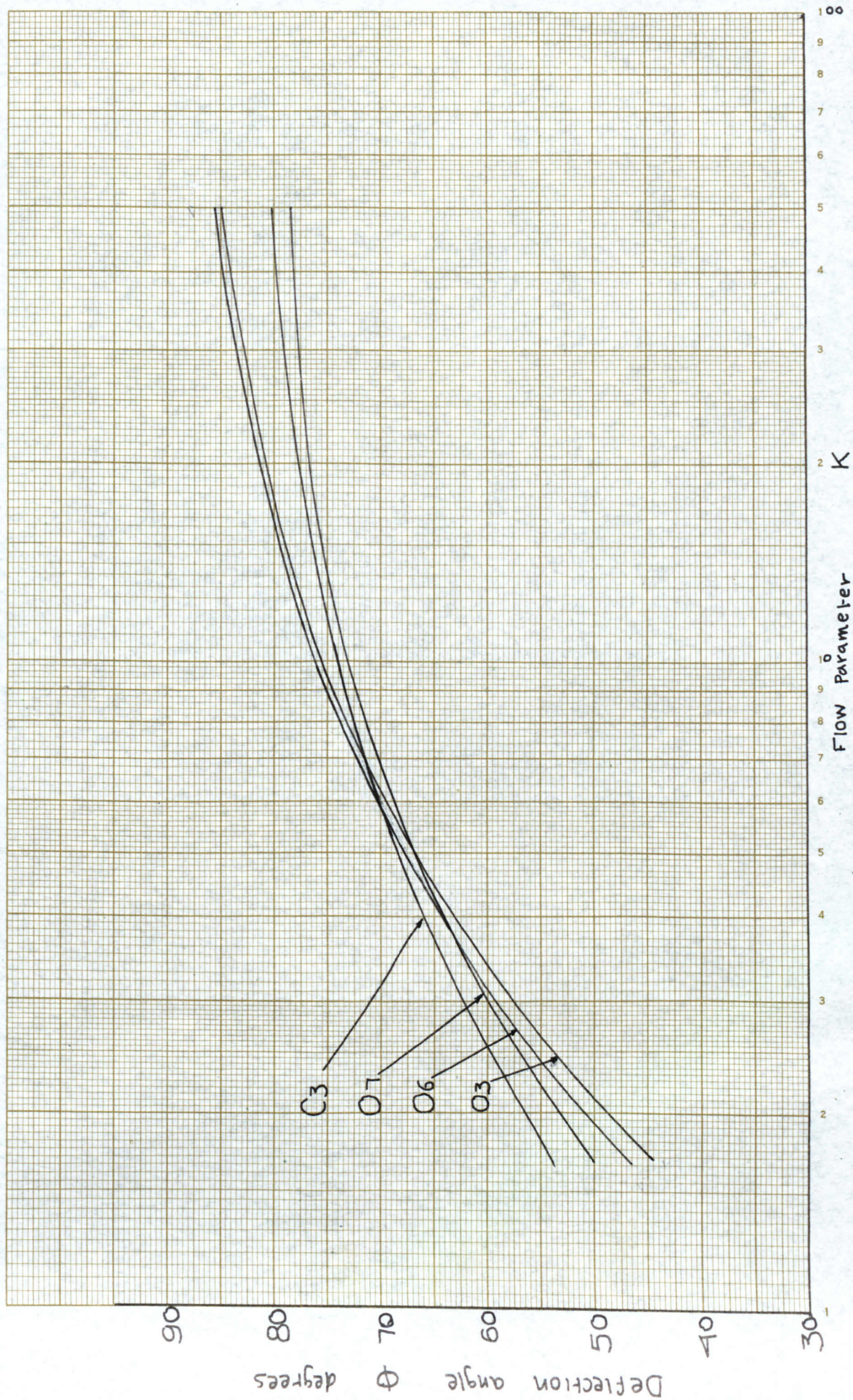
FIG. 68



Discharge coefficient and jet deflection for Oval slots. ($a=0.250$, $b=1.850$, $a^*=0.252$)



Discharge coefficient for Oval slots • (Area ratio = 0.2520)



Jet deflection for Oval slots. (Area ratio = 0.2520)

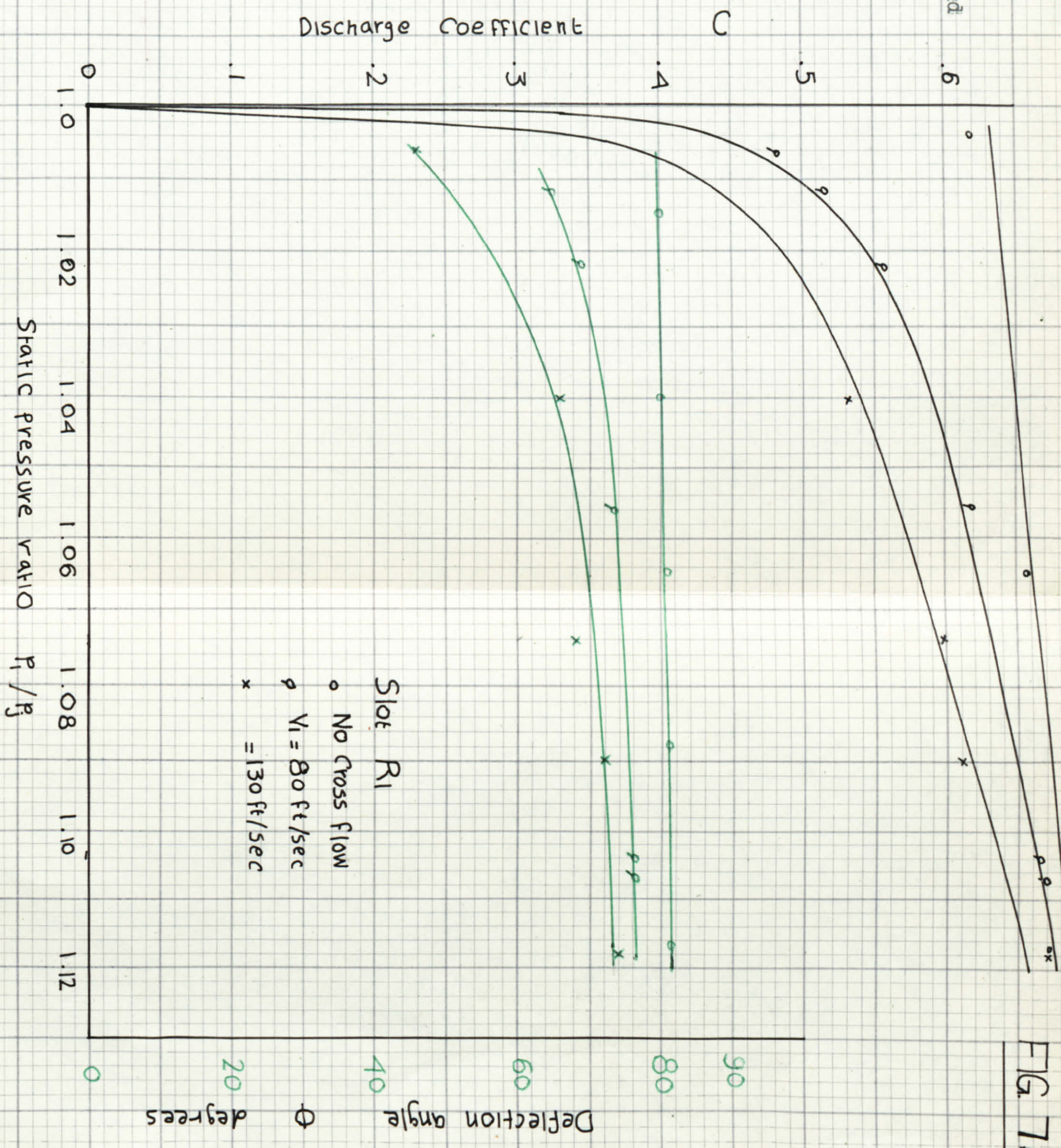
FIG. 71

Discharge coefficient and
jet deflection for

Rectangular slots •

$a = .2061 \text{ in.}$, $b = .412 \text{ in.}$

$\alpha^* = .0595$



Discharge coefficient and
jet deflection for

Rectangular slots .

$a = .295$ in. , $b = .591$ in.

$u_0 = .1220$

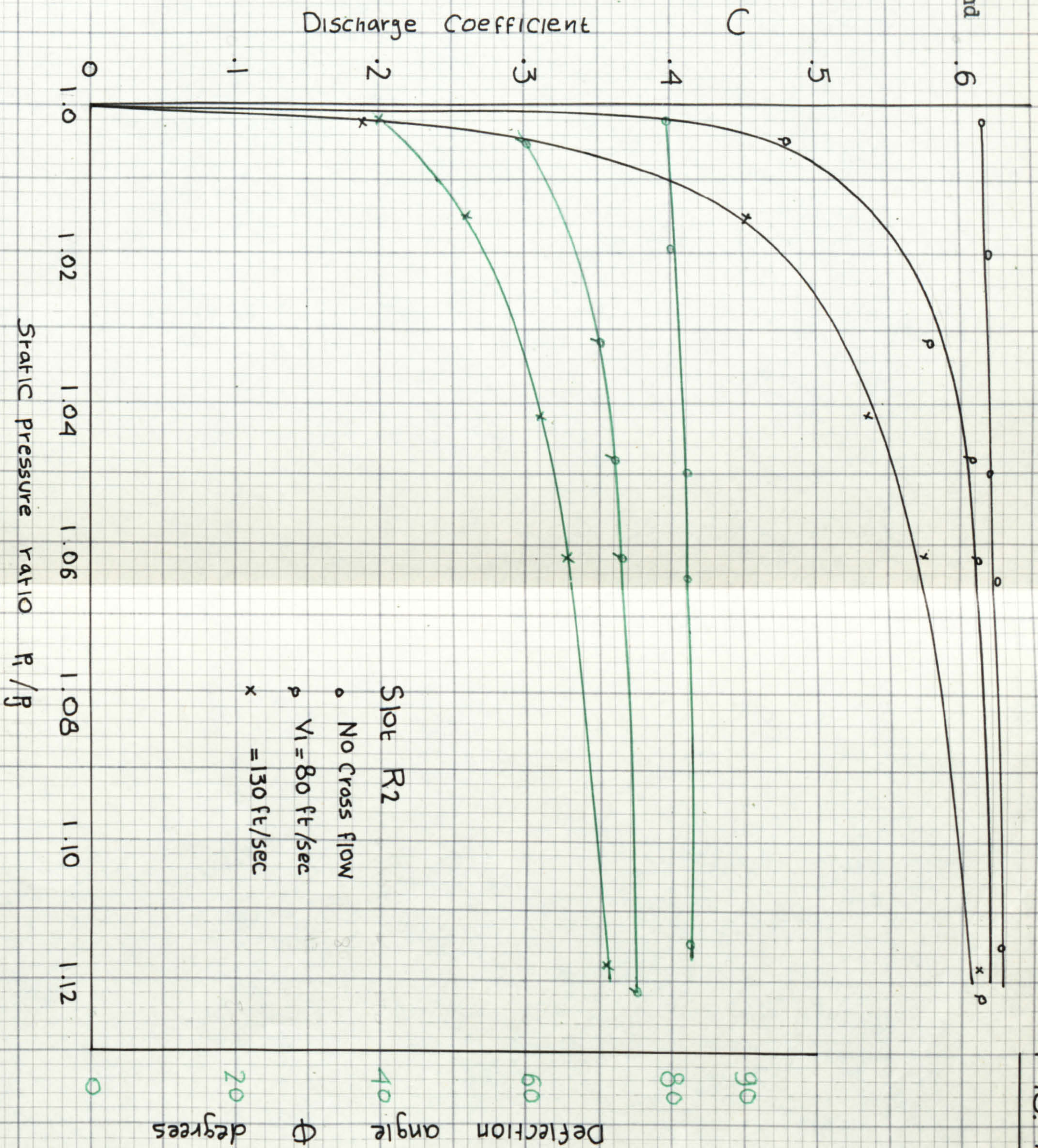


FIG. 73

Discharge coefficient and
jet deflection for
Rectangular slots .

$a = .500$ in. , $b = 1.00$ in.

$a^* = .2500$

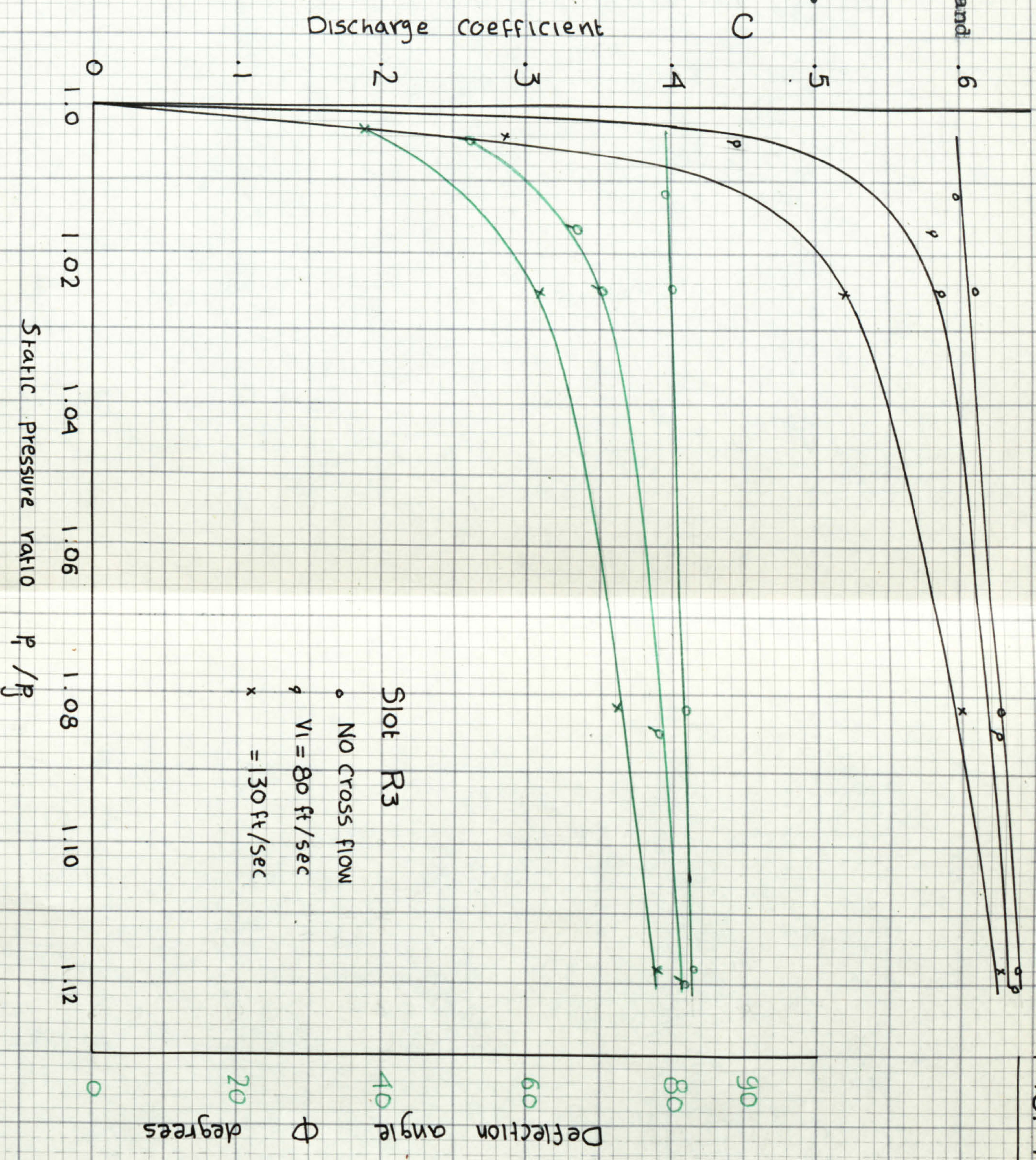
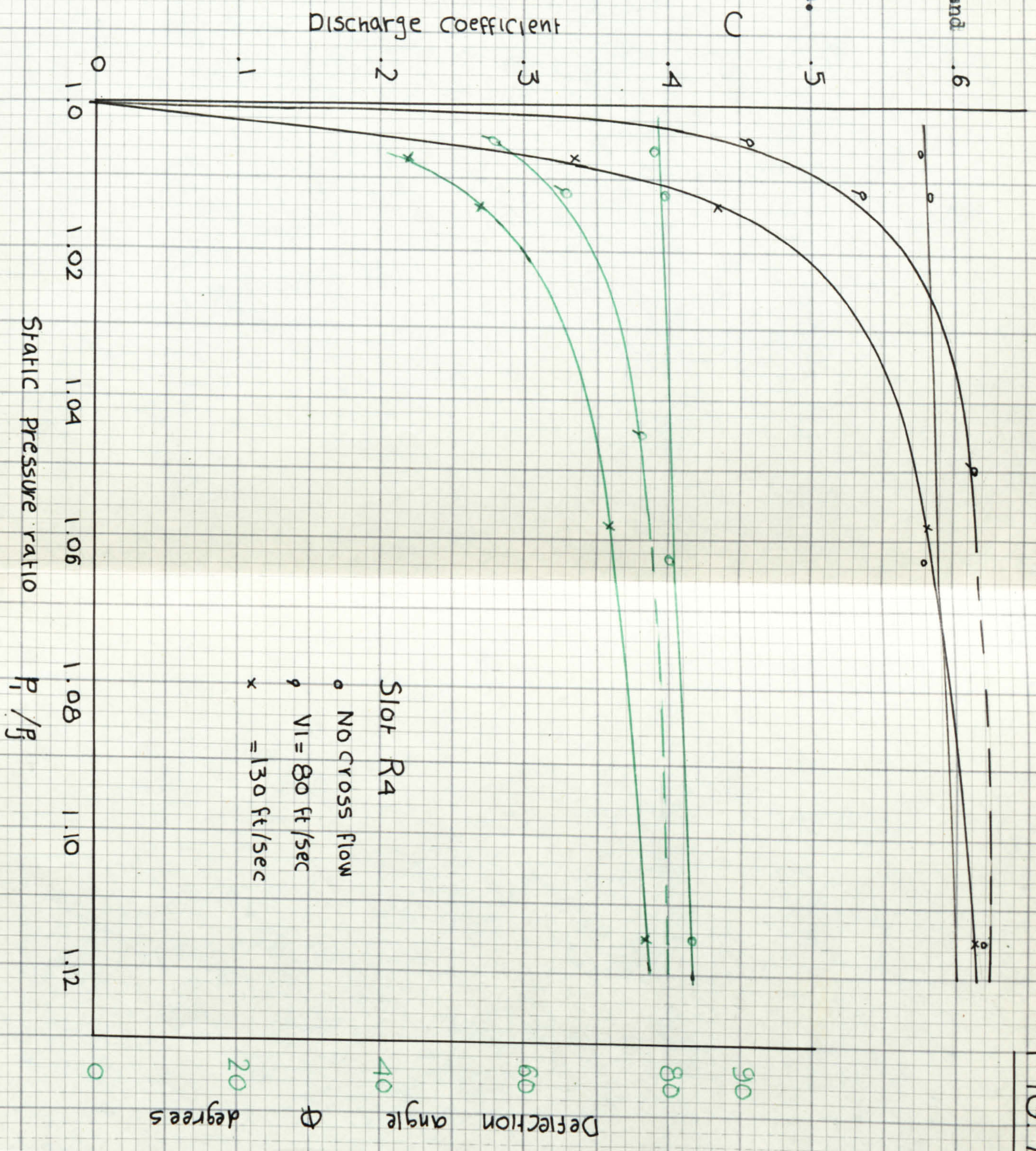


FIG. 74

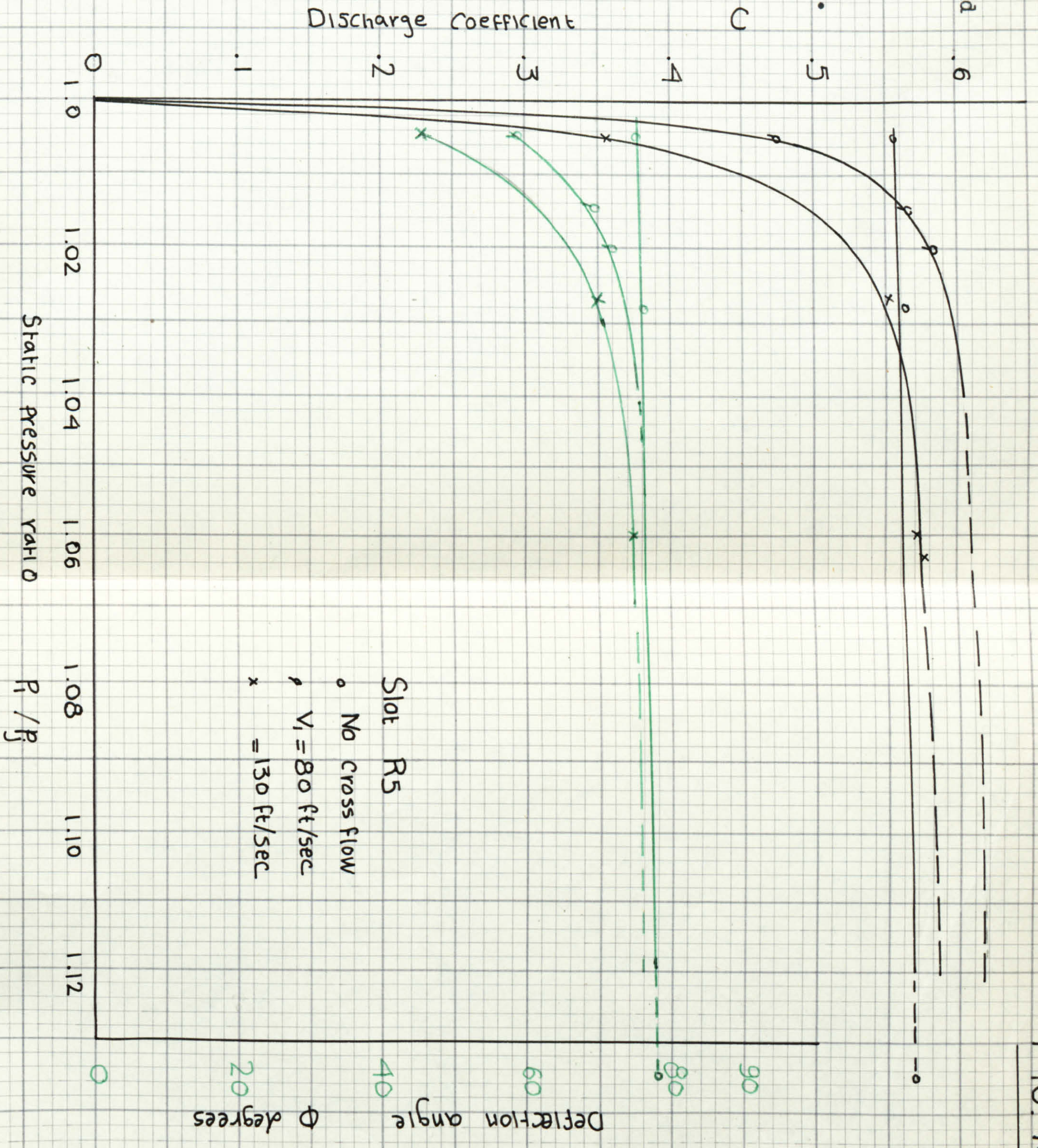
Discharge coefficient and
jet deflection for
Rectangular slots.

$a = .620$ in., $b = 1.240$ in.
 $a^* = .3840$



Discharge coefficient and
jet deflection for
Rectangular slots •

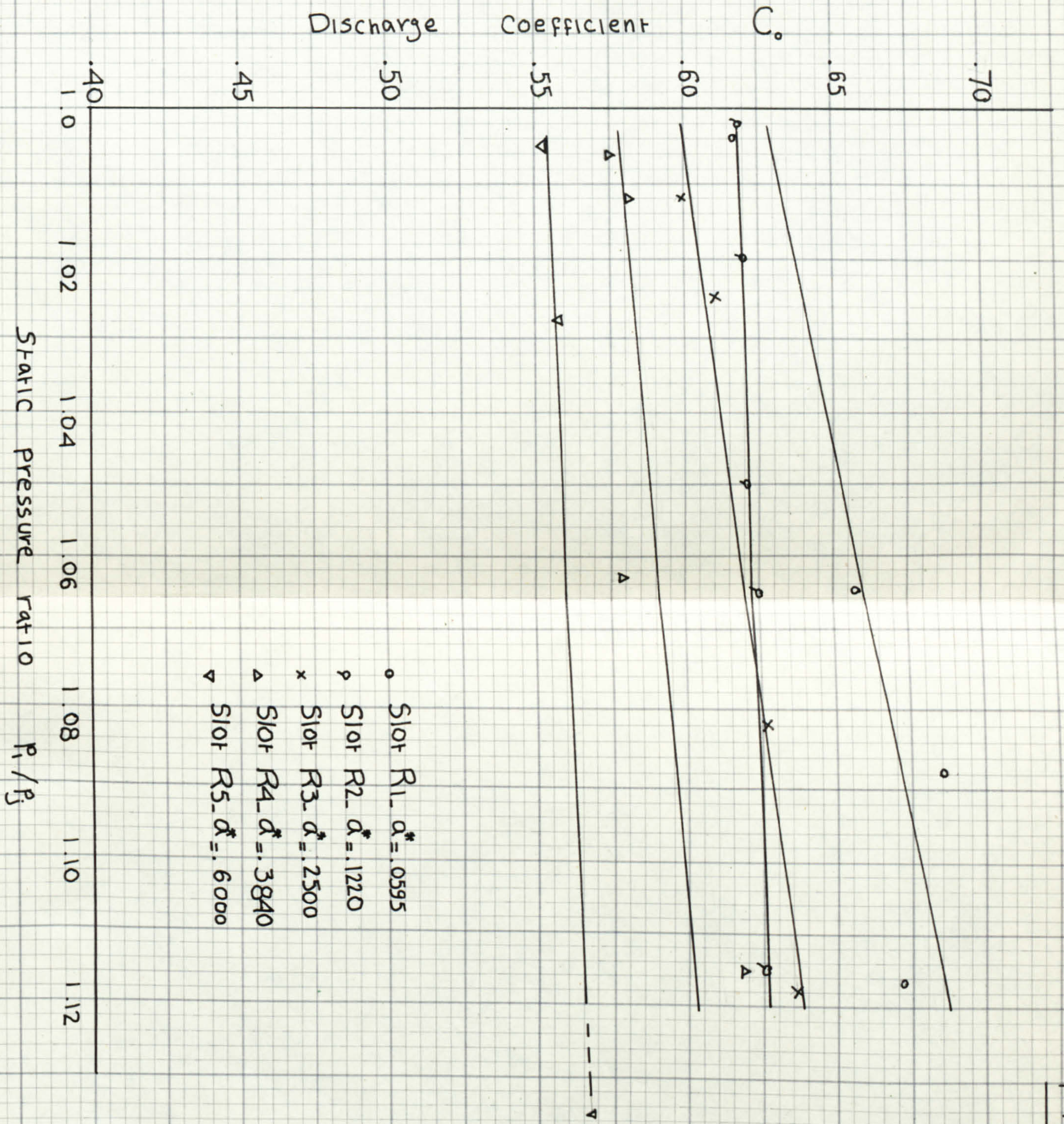
$a = 1.00$ in., $b = 2.00$ in.
 $Re^* = 600$



Discharge coefficient
for Rectangular slots.

Aspect ratio = 2.0

No cross flow.



Deflection angle for

Rectangular slots •

Aspect ratio = 2.0

No cross flow

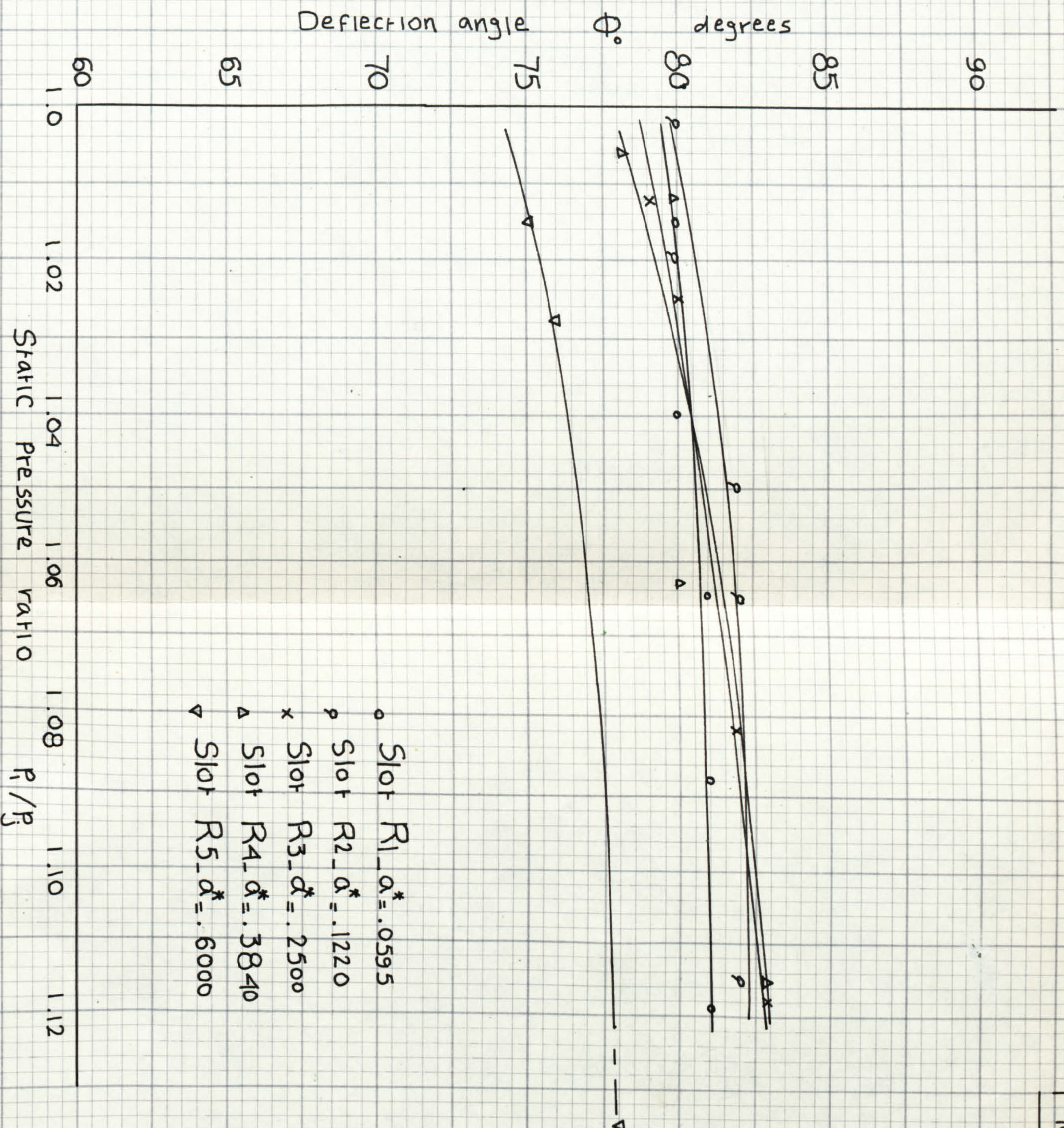


FIG. 78

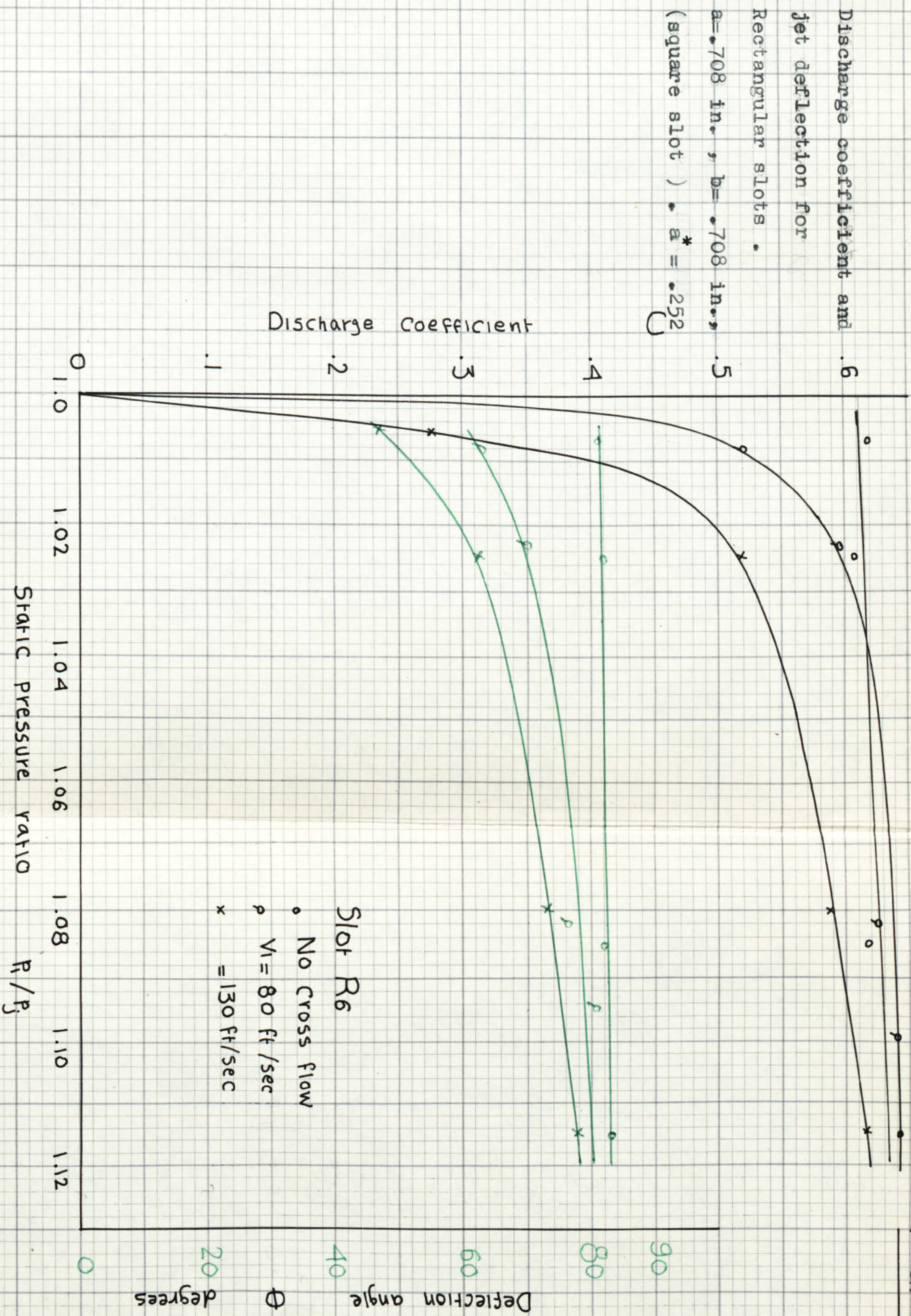


FIG. 79

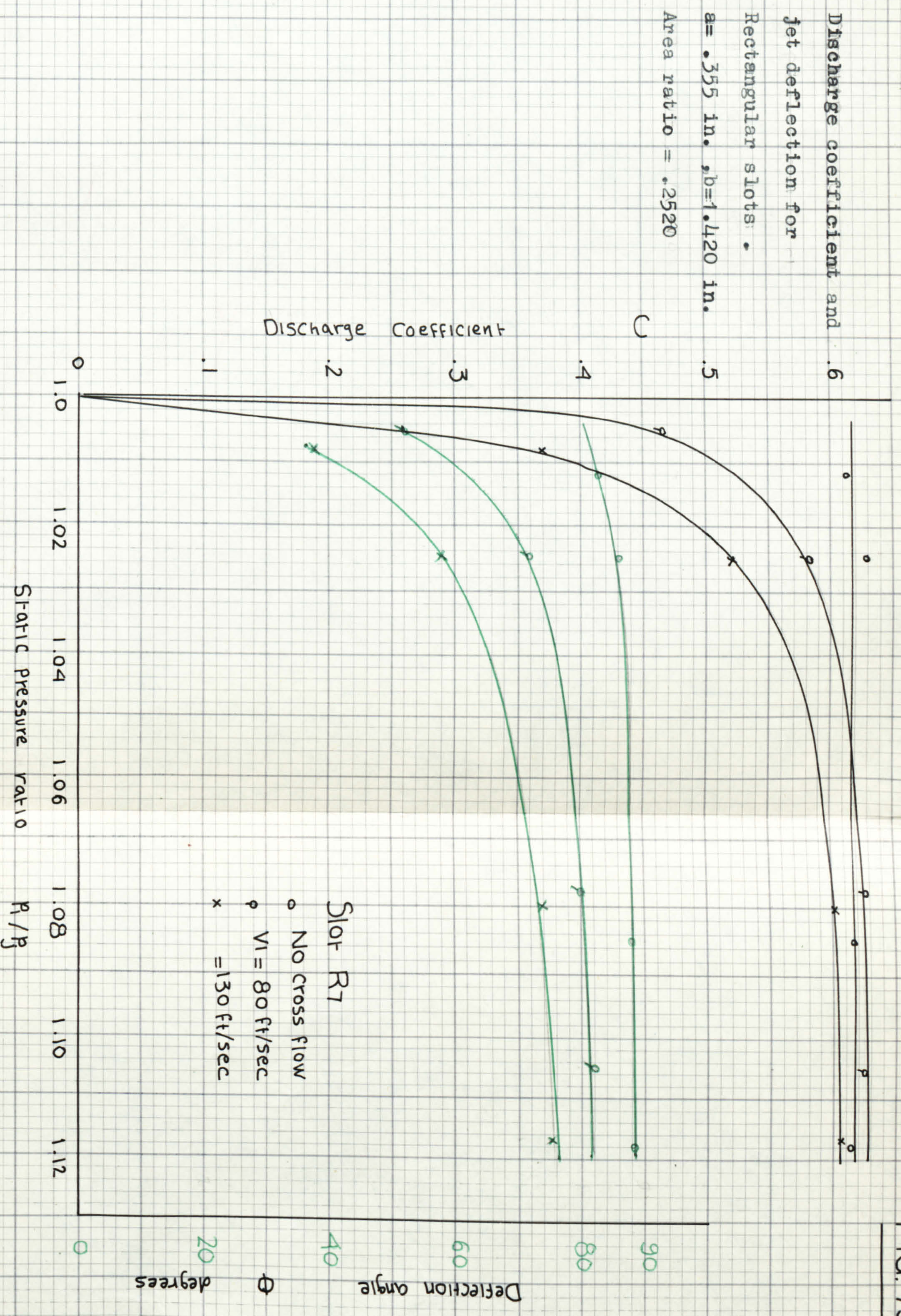
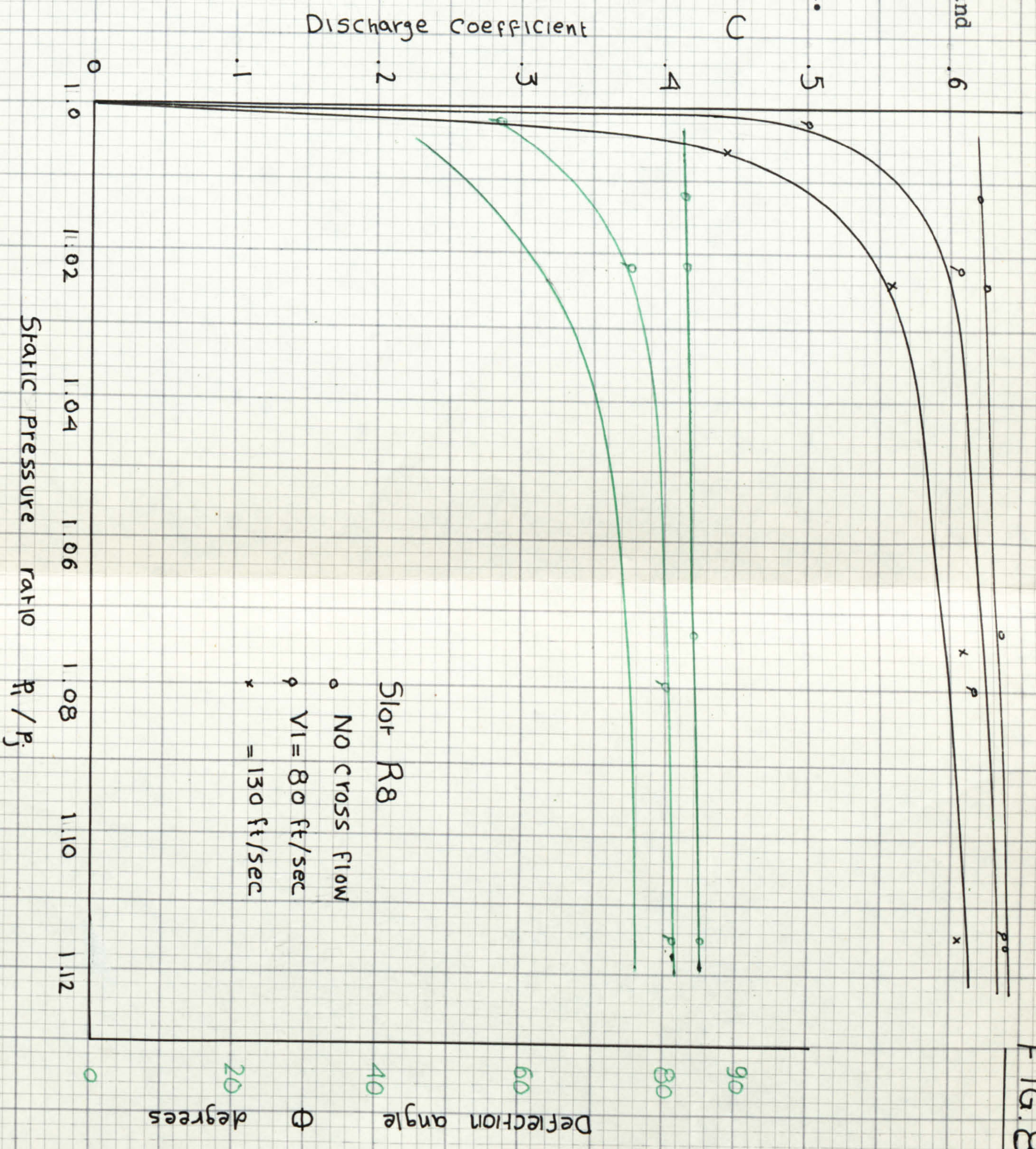


FIG. 80

Discharge coefficient and
jet deflection for
Rectangular slots .

$a = .250$ in. , $b = 2.00$ in.

Area ratio = .2500



Discharge coefficient for .70

Rectangular slots .

Area ratio = .2520

No cross flow .

Discharge Coefficient

C_d

.40

.45

.50

.55

.60

.65

1.0

1.02

1.04

1.06

1.08

1.10

1.12

Static pressure ratio

P_i / P_j



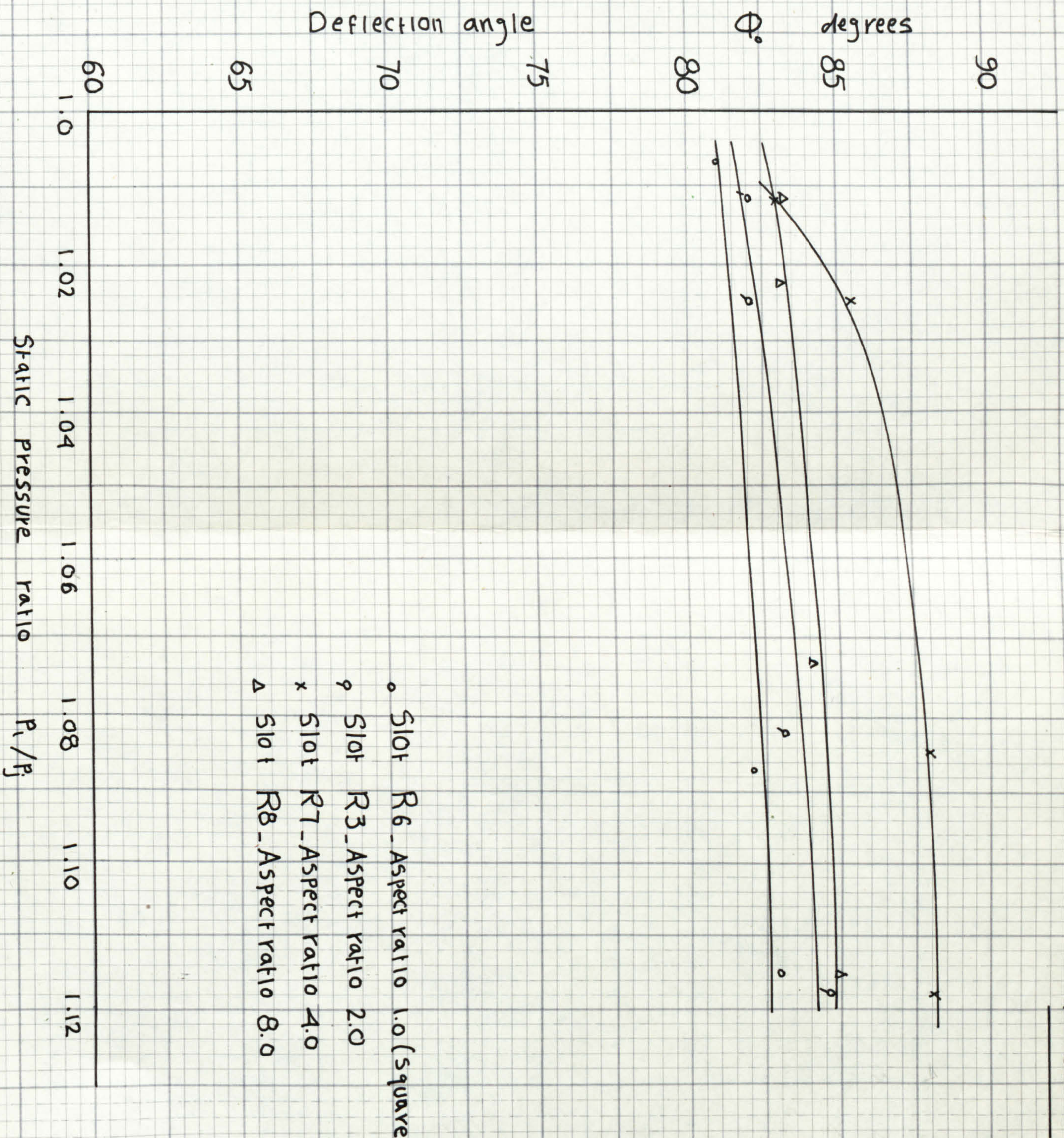
- o Slot R6 - Aspect ratio 1.0 (square)
- p Slot R3 - Aspect ratio 2.0
- x Slot R7 - Aspect ratio 4.0
- Δ Slot R8 - Aspect ratio 8.0

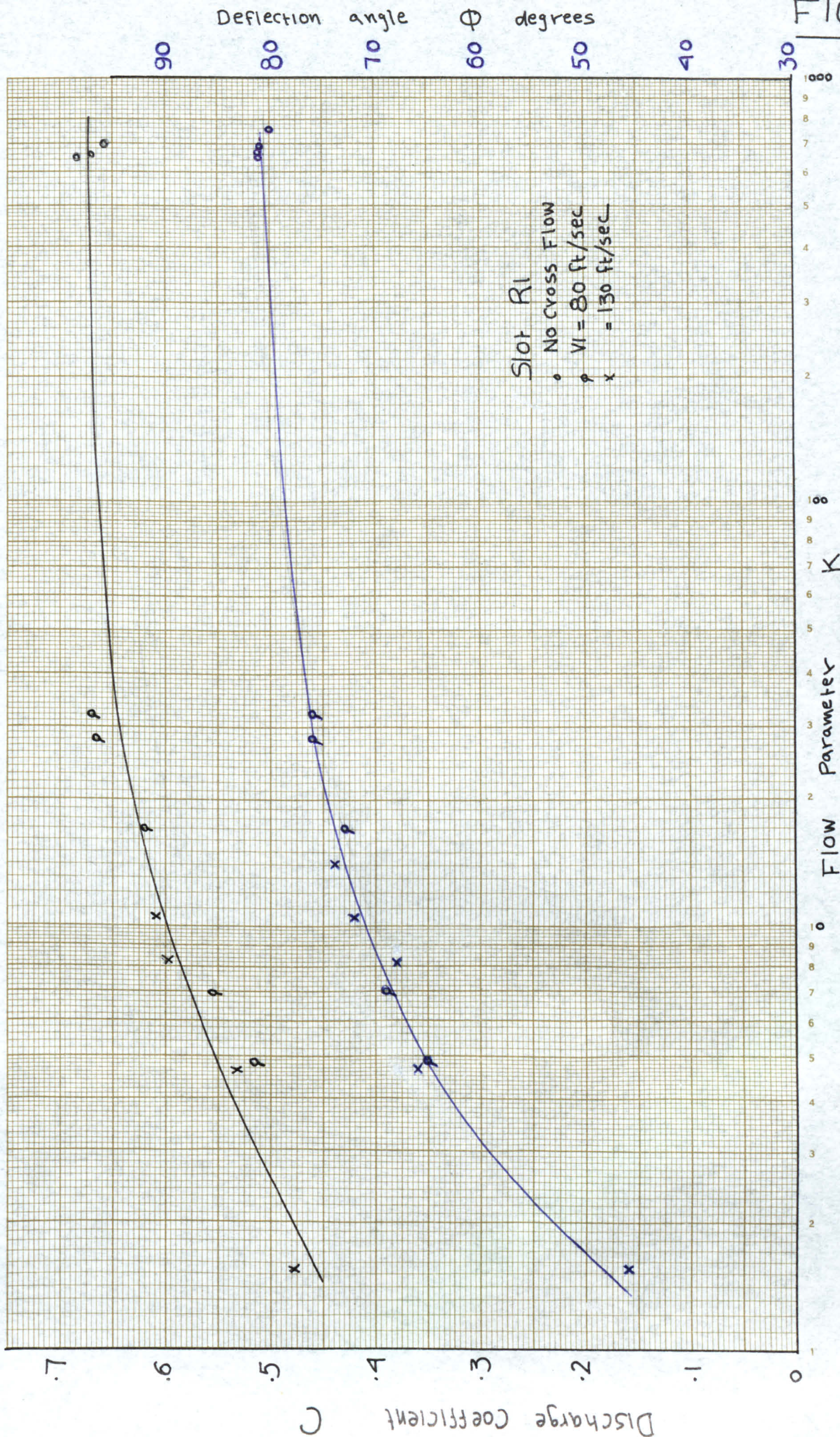
Deflection angle for

Rectangular slots .

Area ratio = .2520

No cross flow .

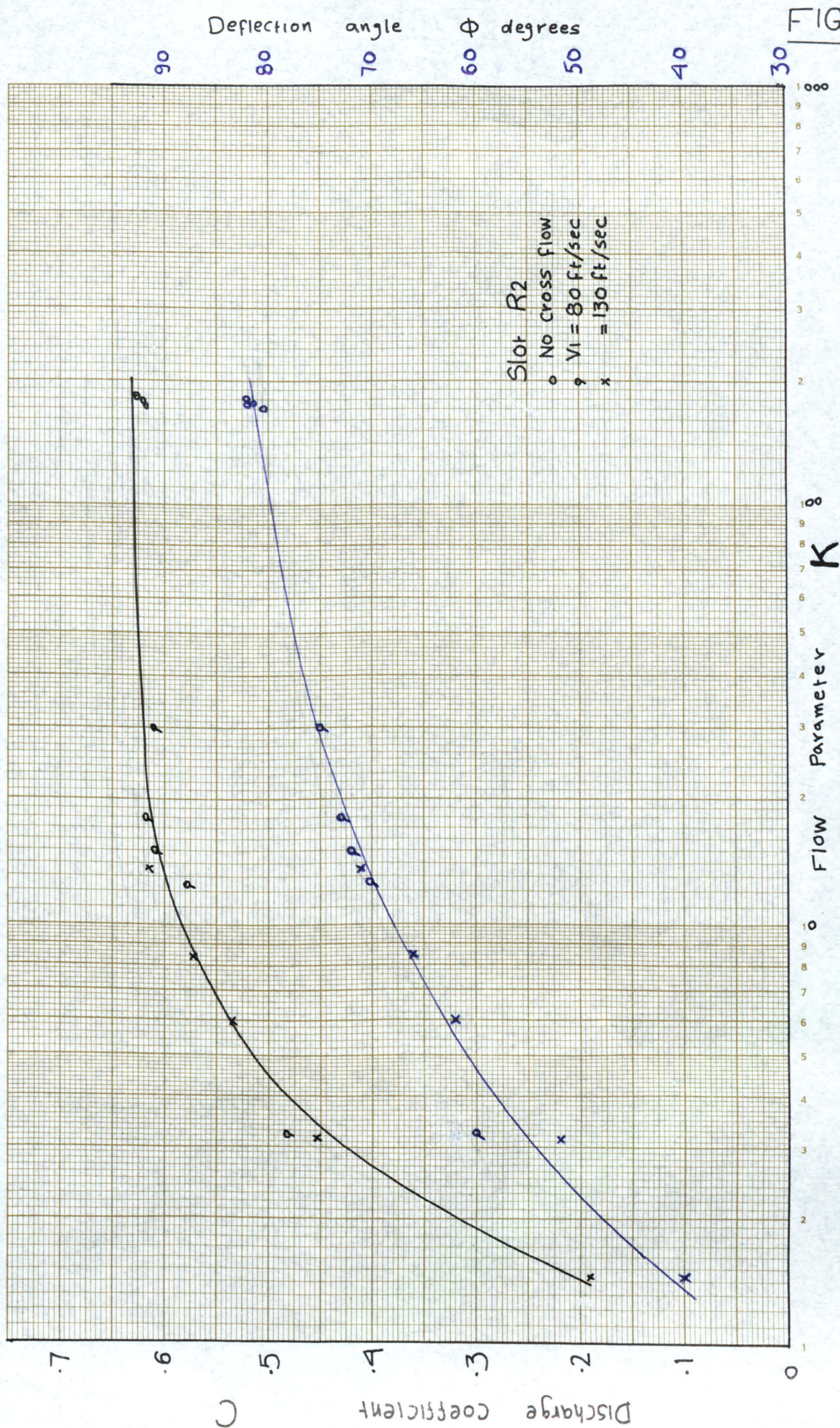


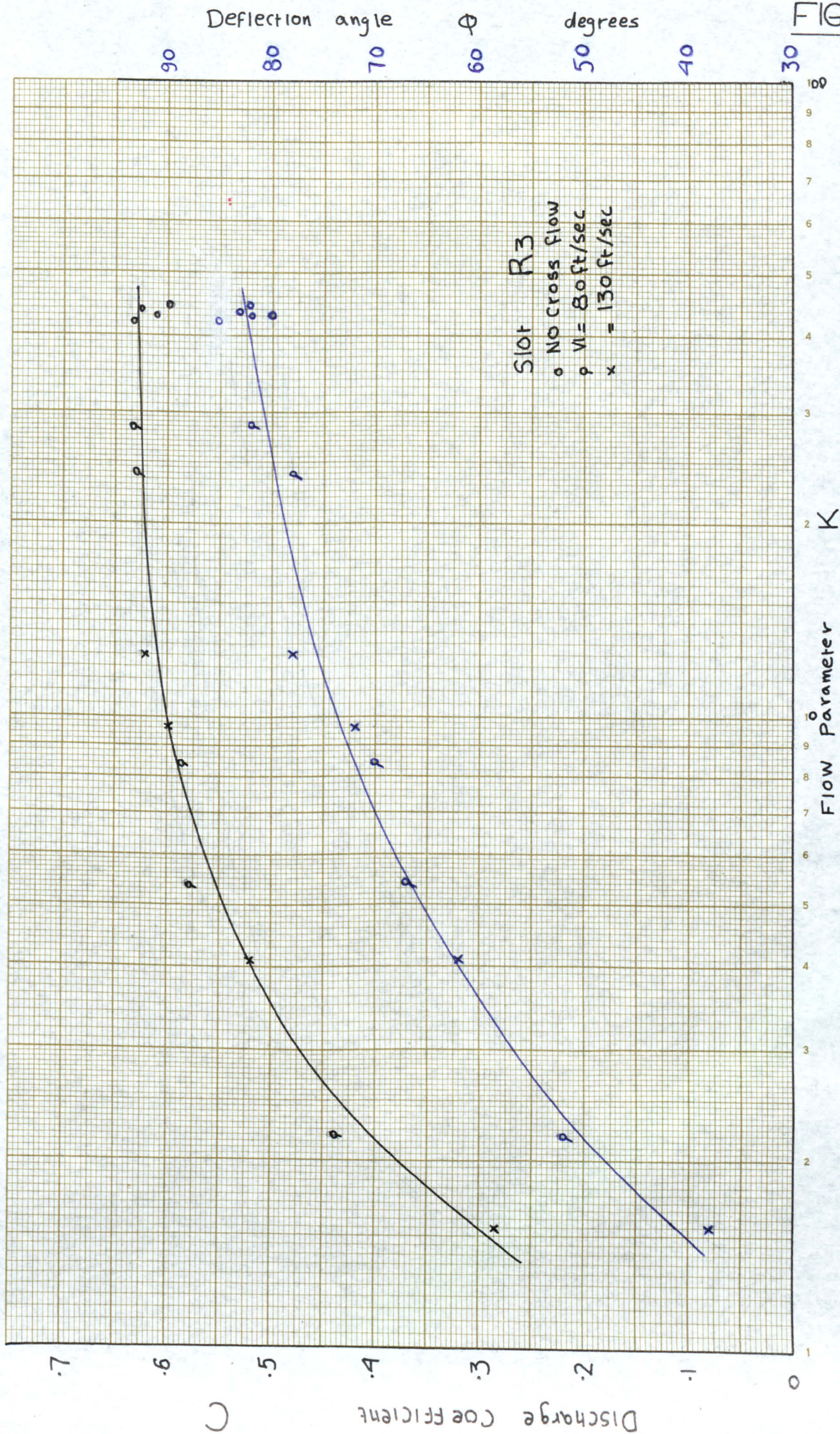


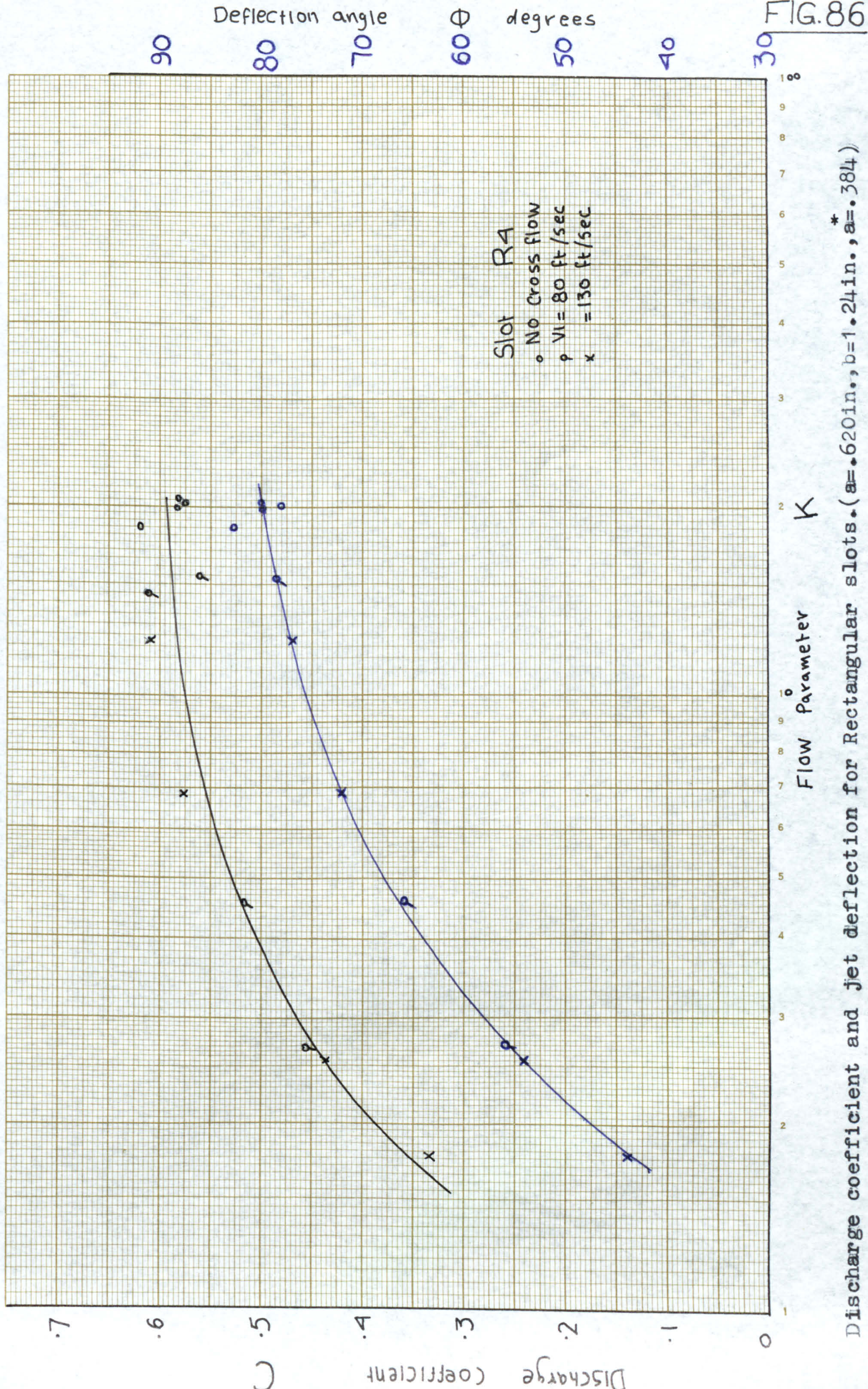
Deflection angle Φ degrees

90 80 70 60 50 40 30

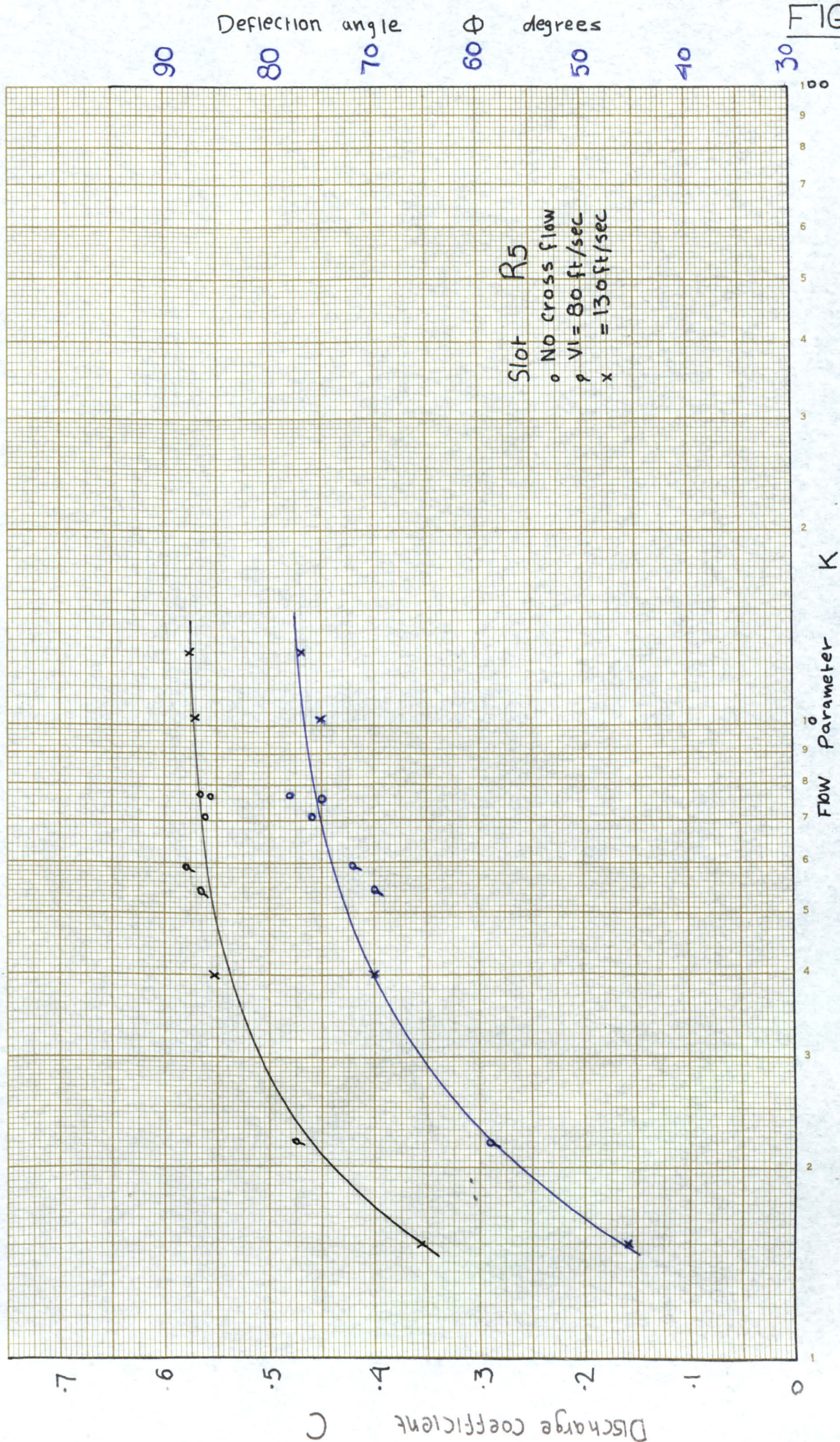
Discharge coefficient and jet deflection for Rectangular slots. ($a=0.206$ in., $b=0.412$ in., $a^*=0.0595$)



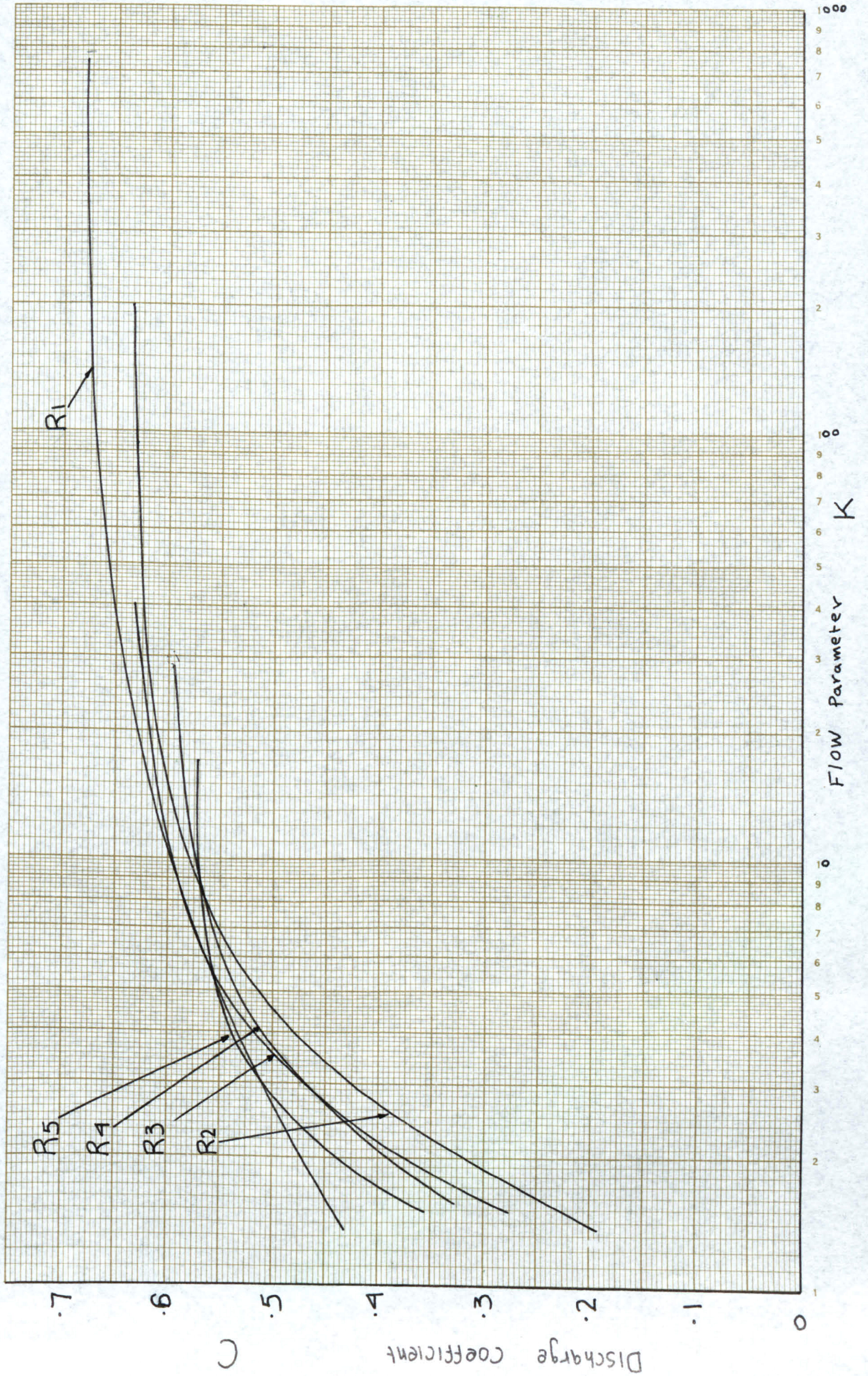




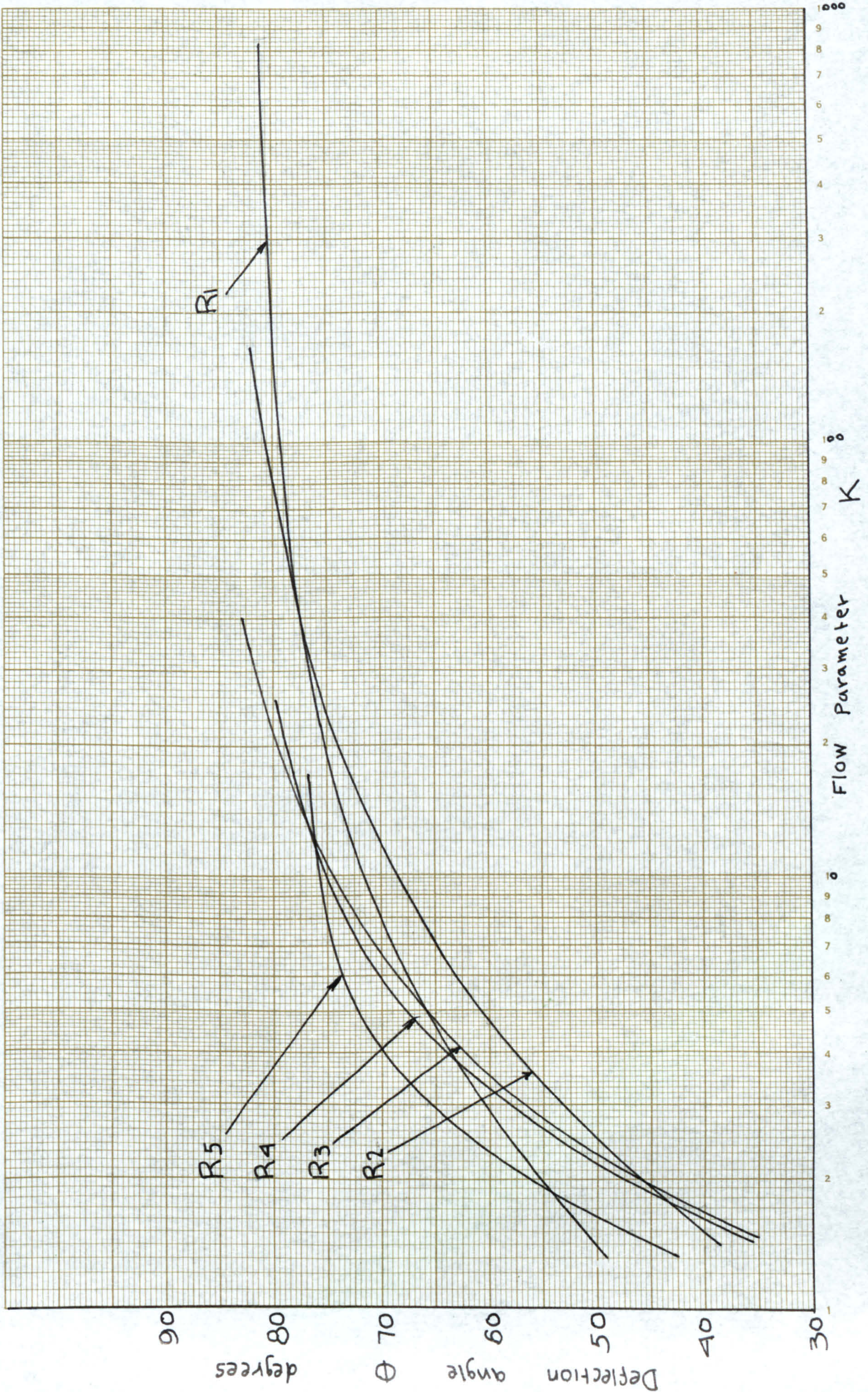
Discharge coefficient and jet deflection for Rectangular slots. ($a=0.620 \text{ in.}$, $b=1.24 \text{ in.}$, $a^*=0.384$)



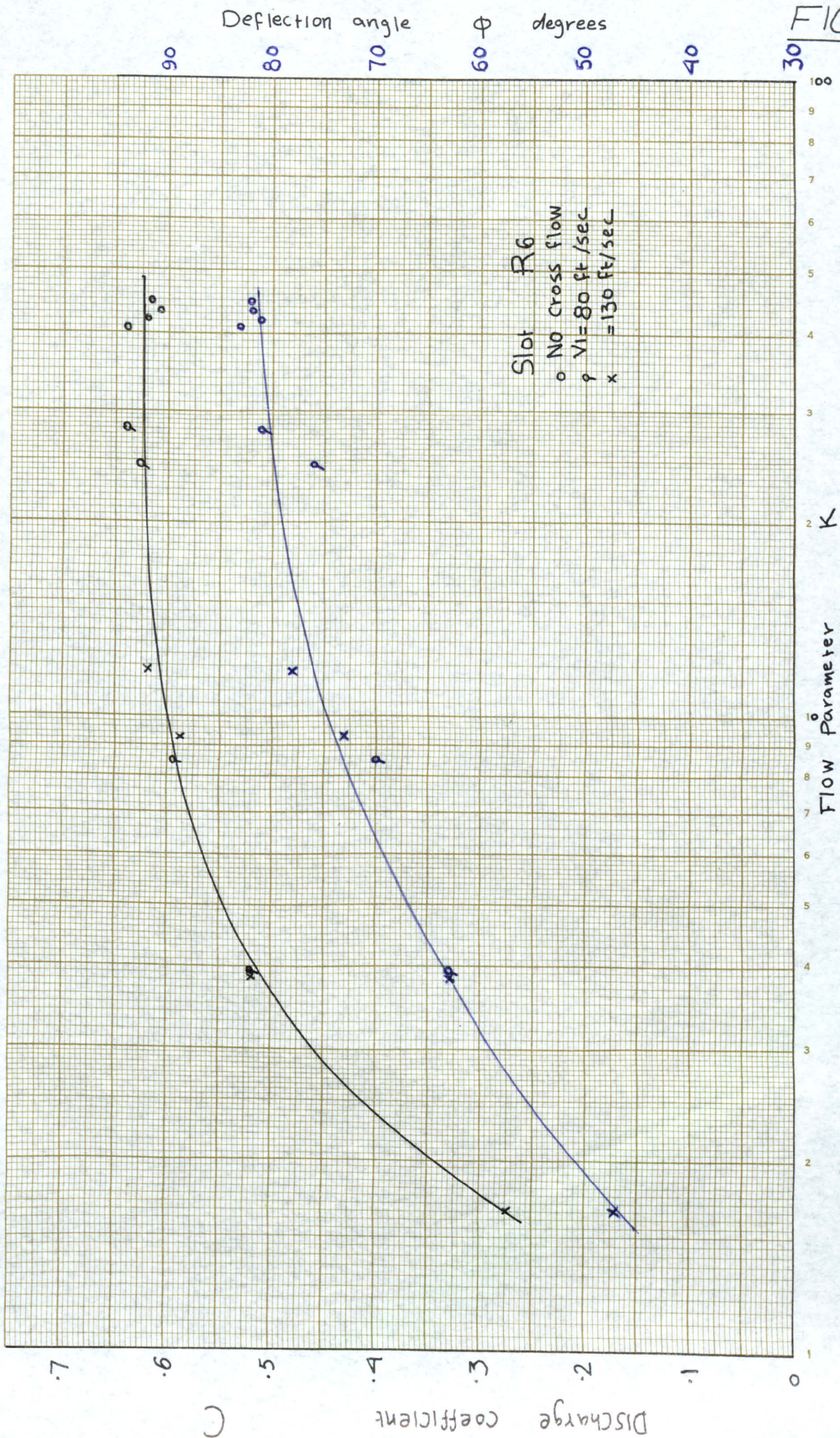
Discharge coefficient C and jet deflection for Rectangular slots. ($a=1.0$ in., $b=2.0$ in., $a^*=600$)



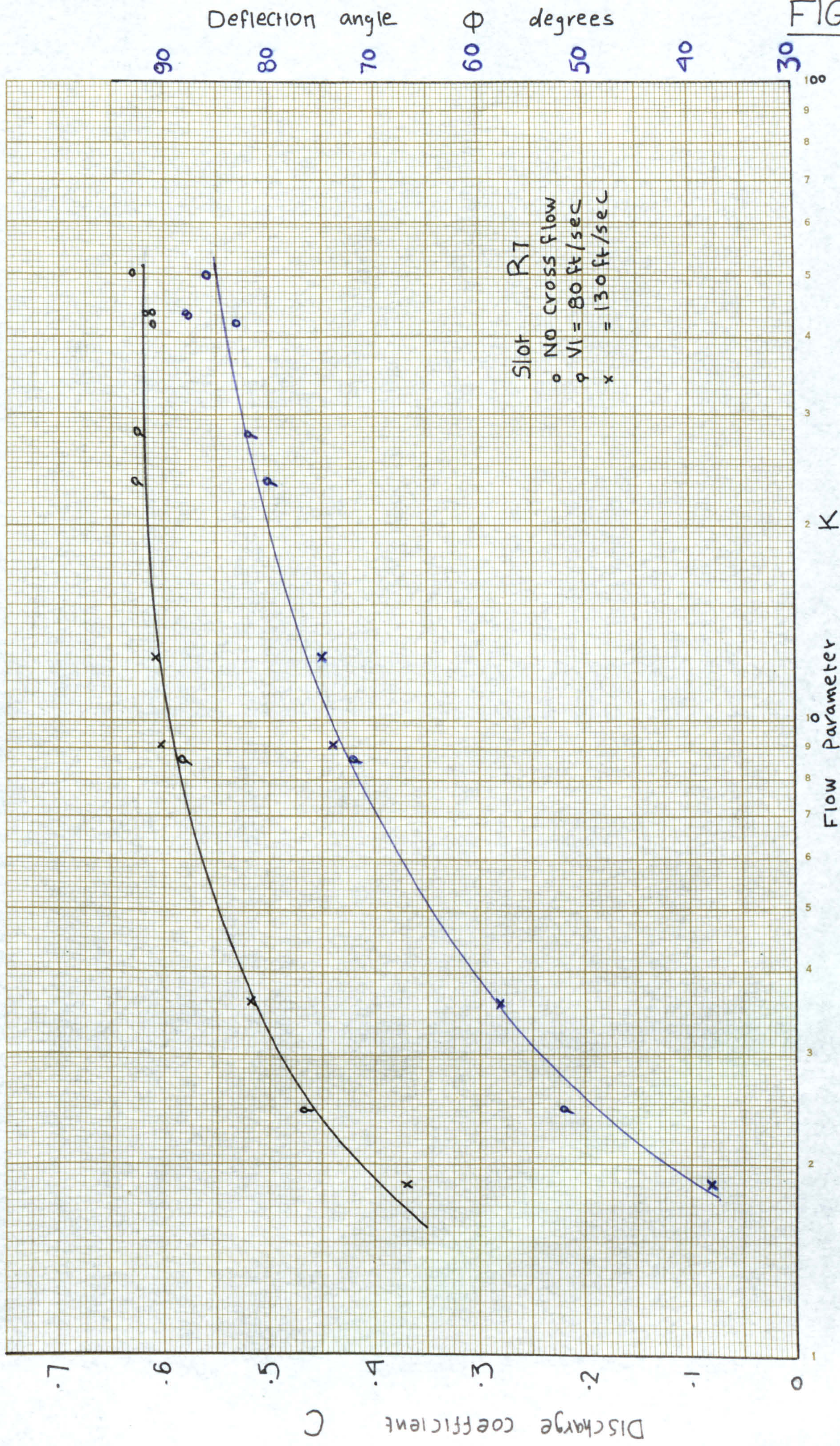
Discharge coefficient for Rectangular slots. (Aspect ratio=2.0)

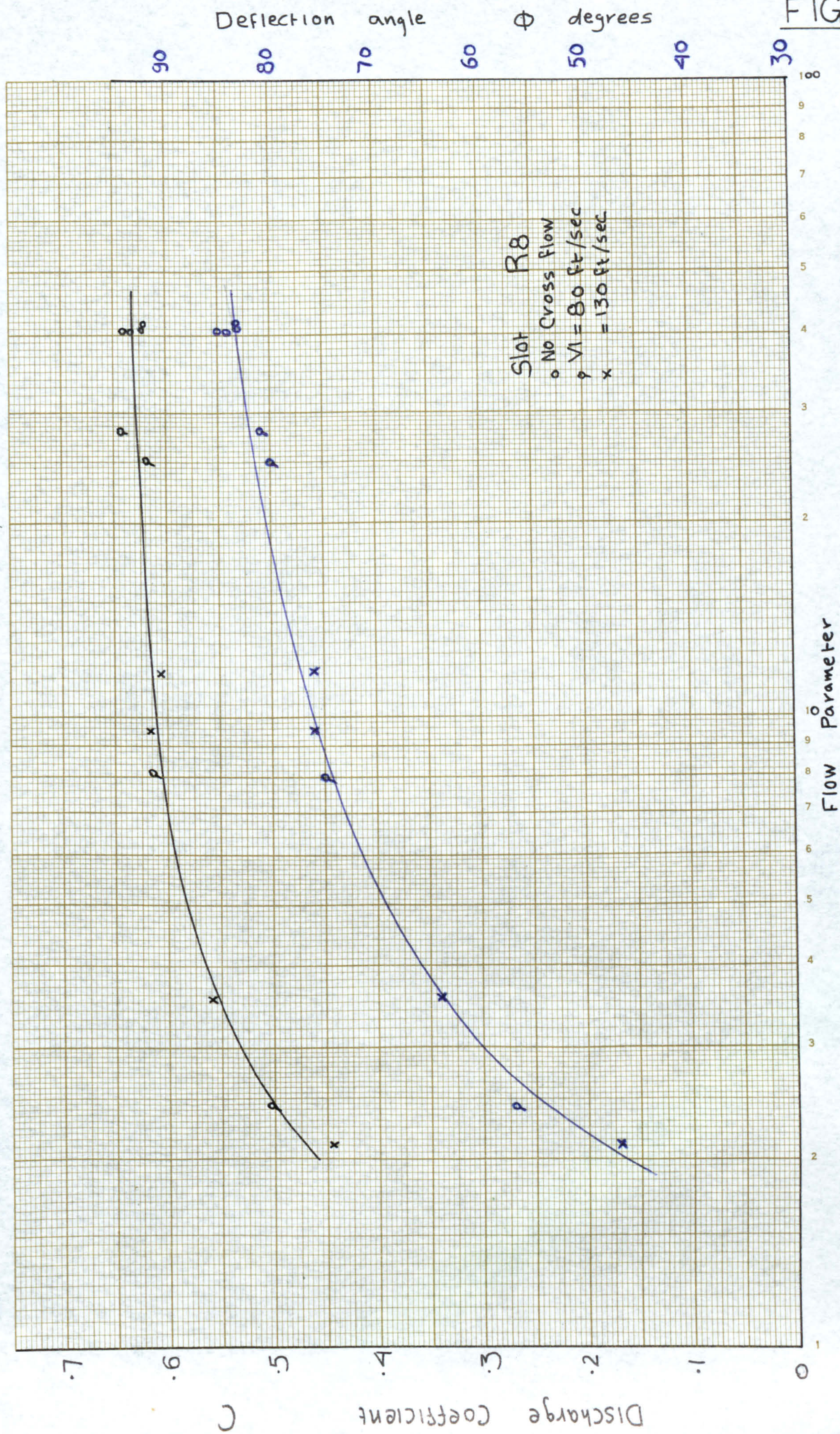


Jet deflection for Rectangular slots. (Aspect ratio = 2.0)

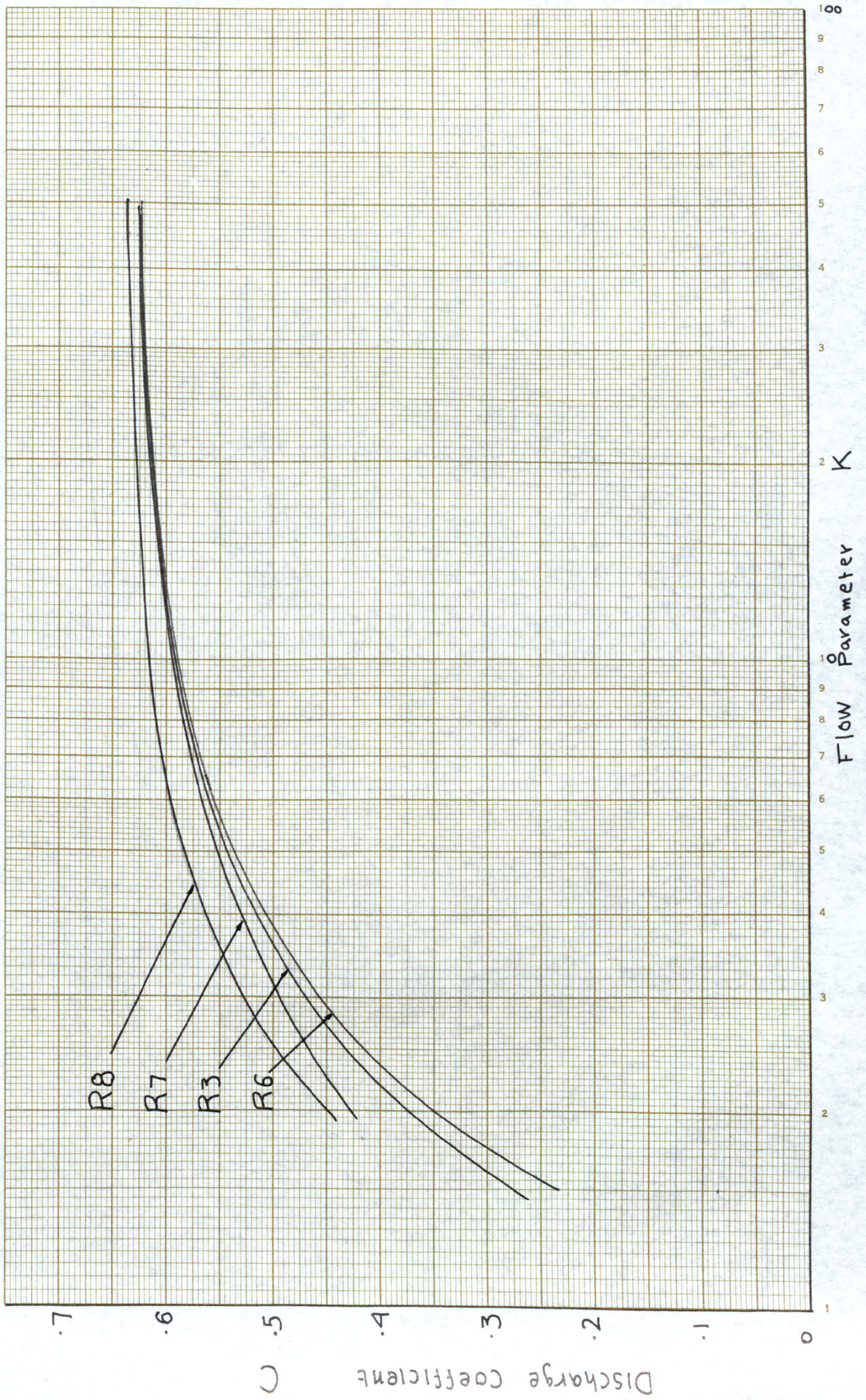


Discharge coefficient and jet deflection for Rectangular slots. ($a = 708 \text{ in.}$, $b = 708 \text{ in.}$, $a^* = 252$)

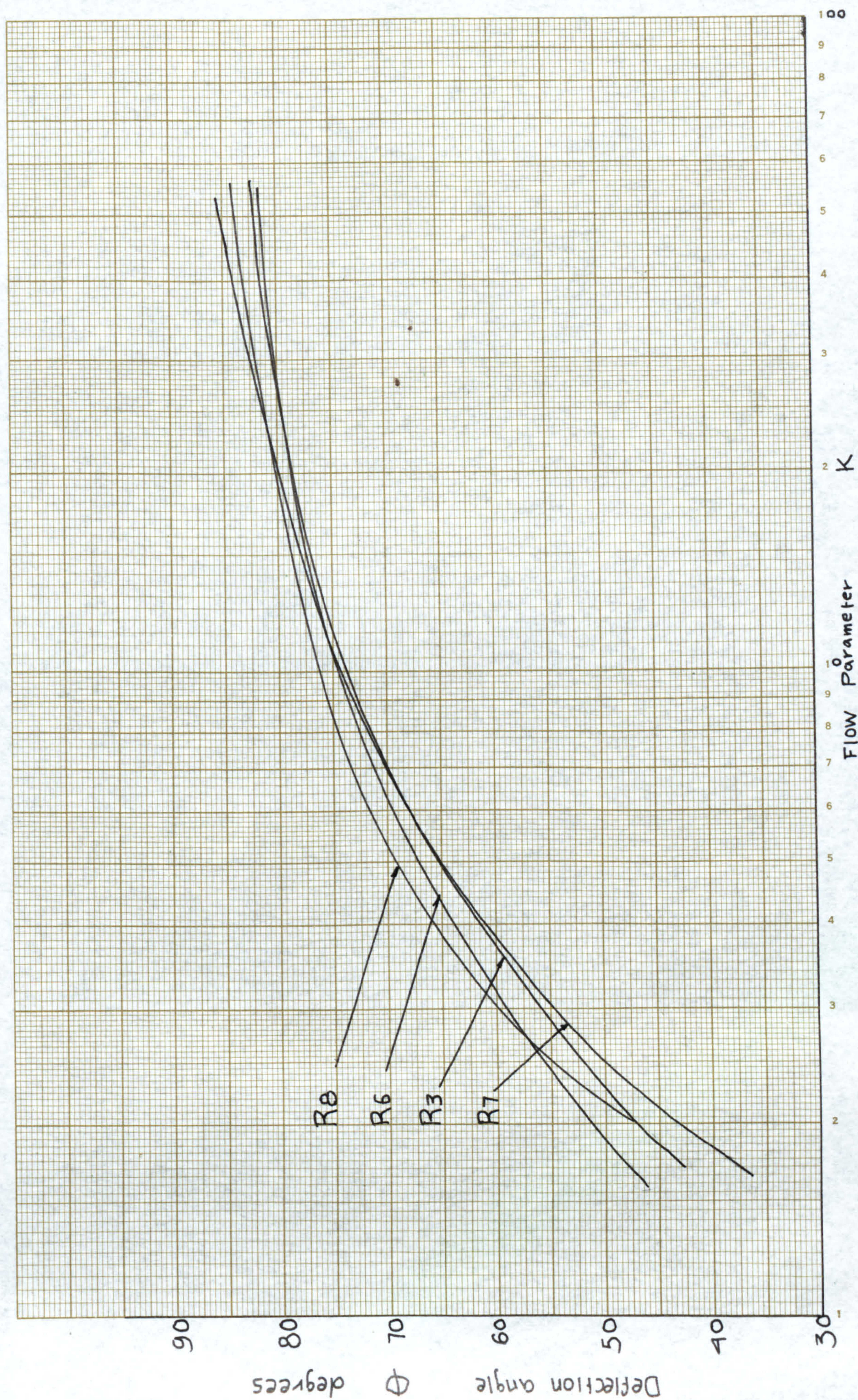




Discharge coefficient and jet deflection for Rectangular slots. ($a = 2.50 \text{ in.}$, $b = 2.0 \text{ in.}$, $a^* = 2.50$)



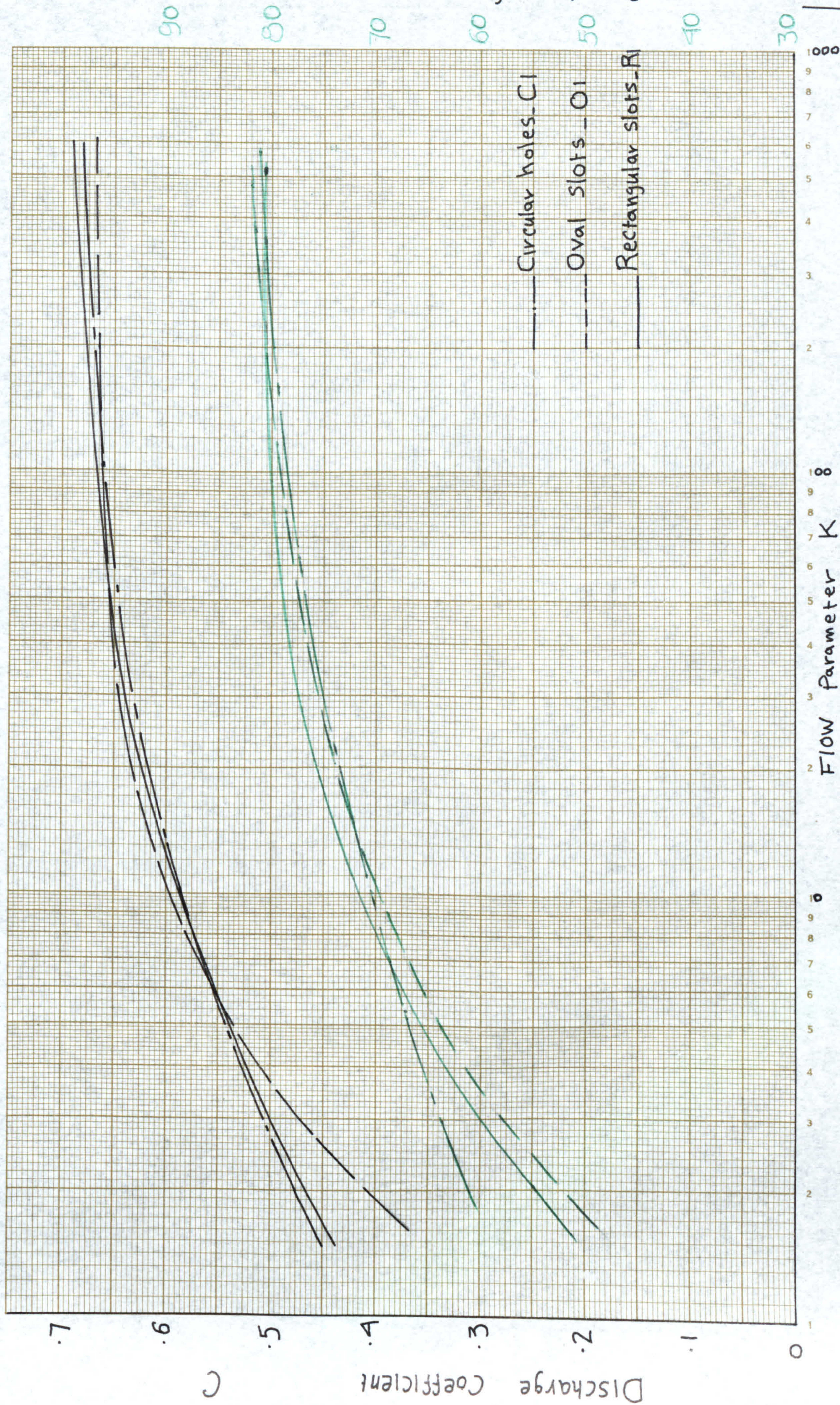
Discharge coefficient for Rectangular slots. (Area ratio = .2520)



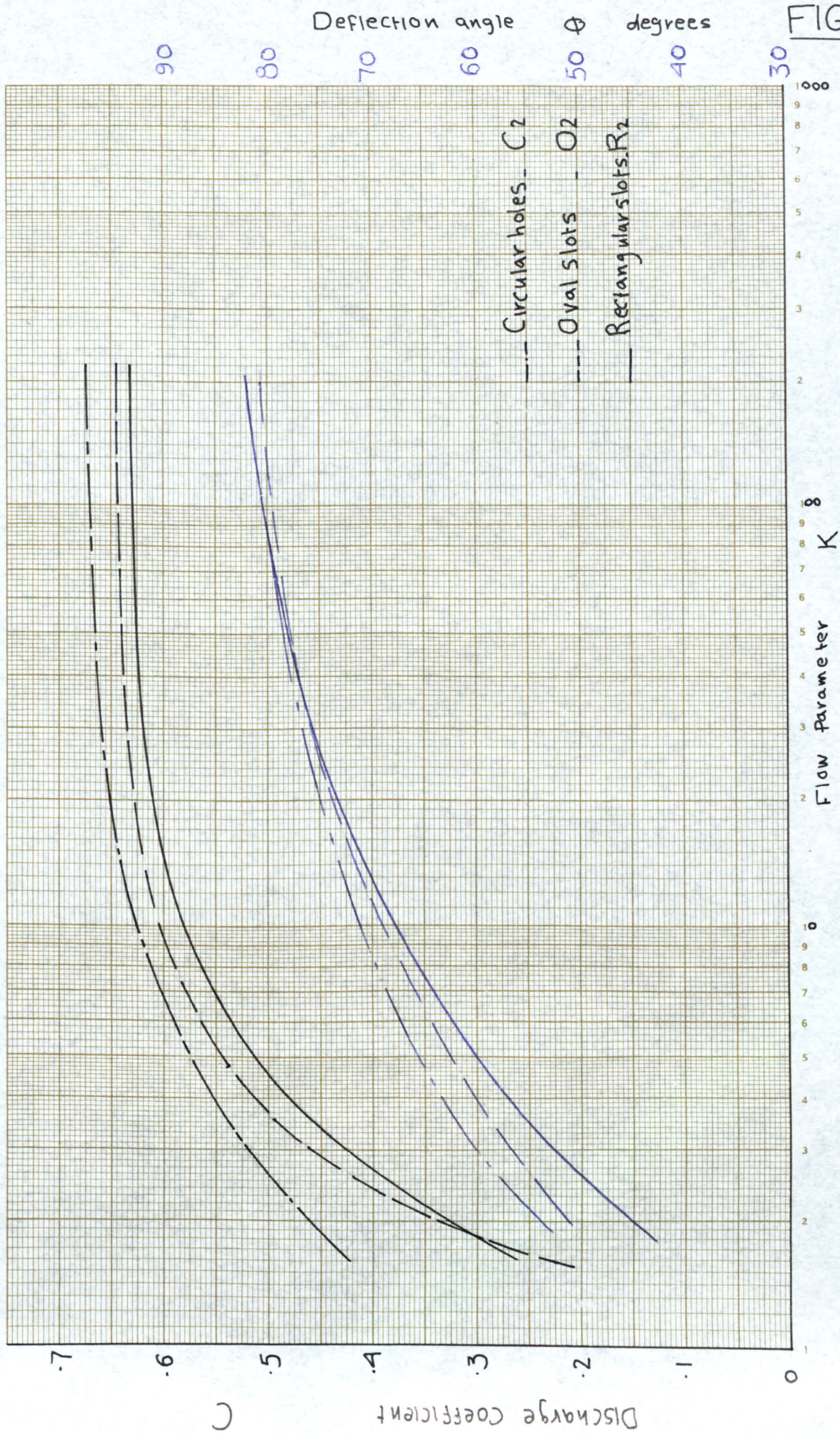
Jet deflection for Rectangular slots. (Area ratio = 0.2520)

Deflection angle ϕ degrees

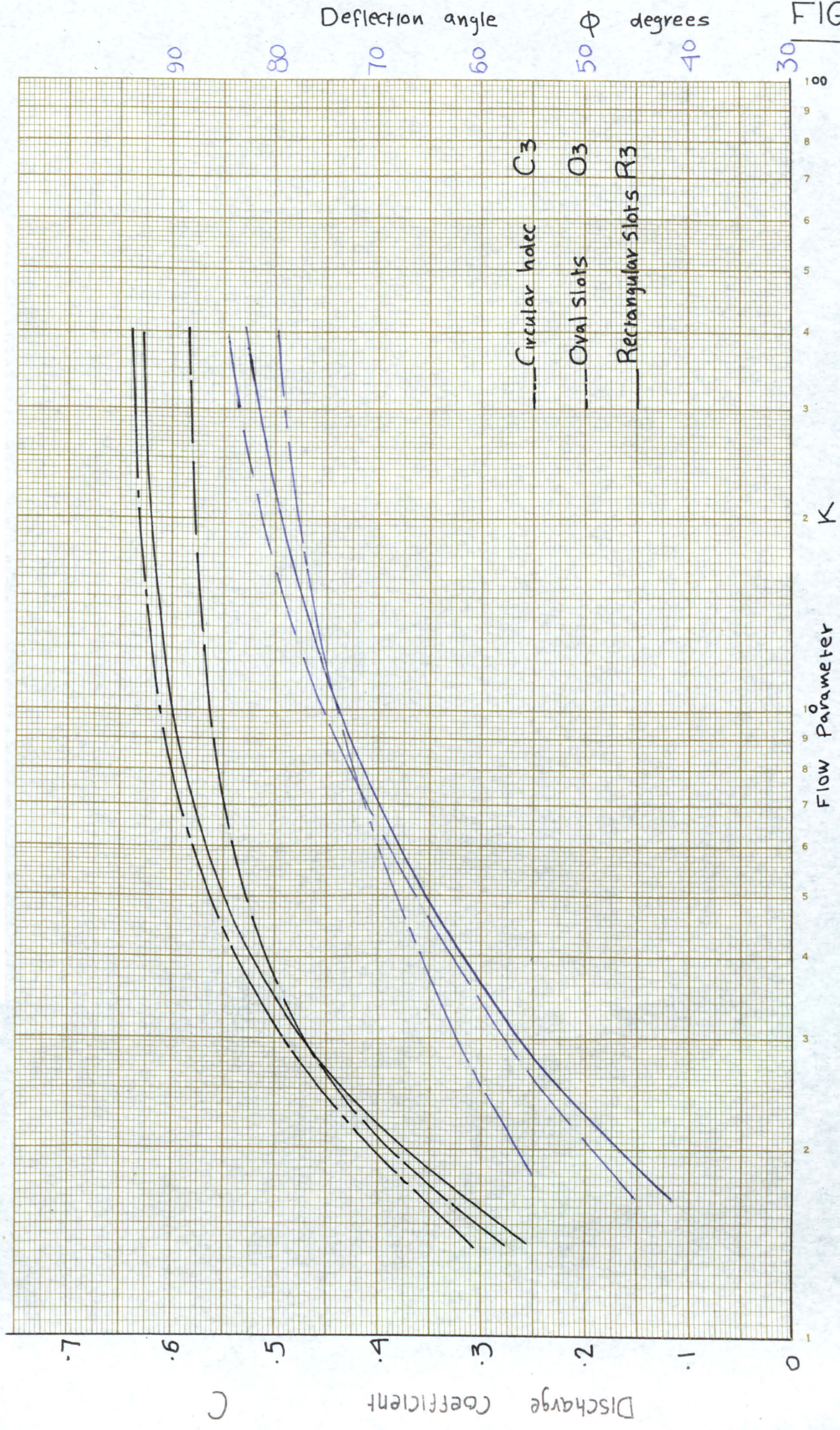
FIG. 95



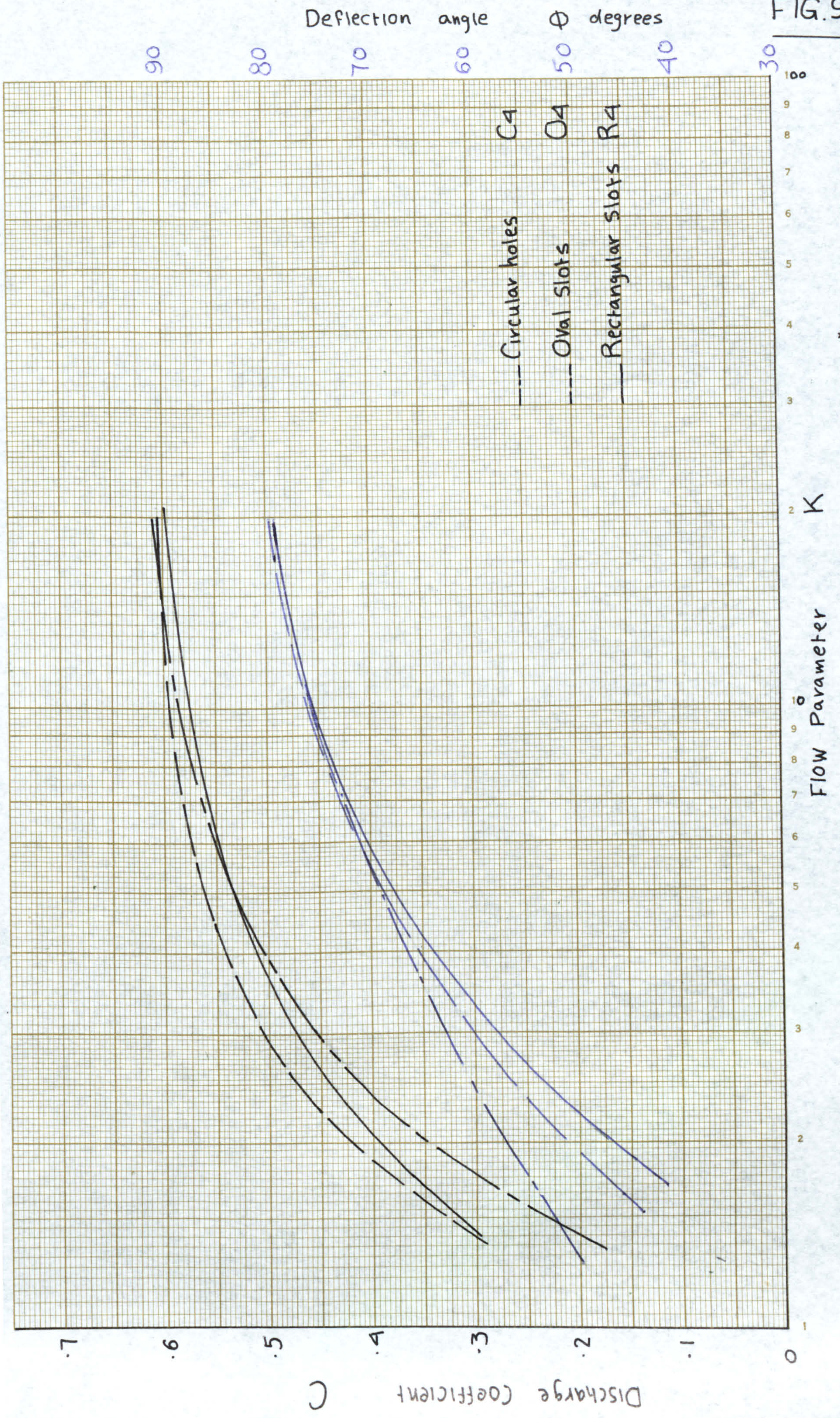
Discharge coefficient and jet deflection for liner holes. ($a^* = 0.0595$)



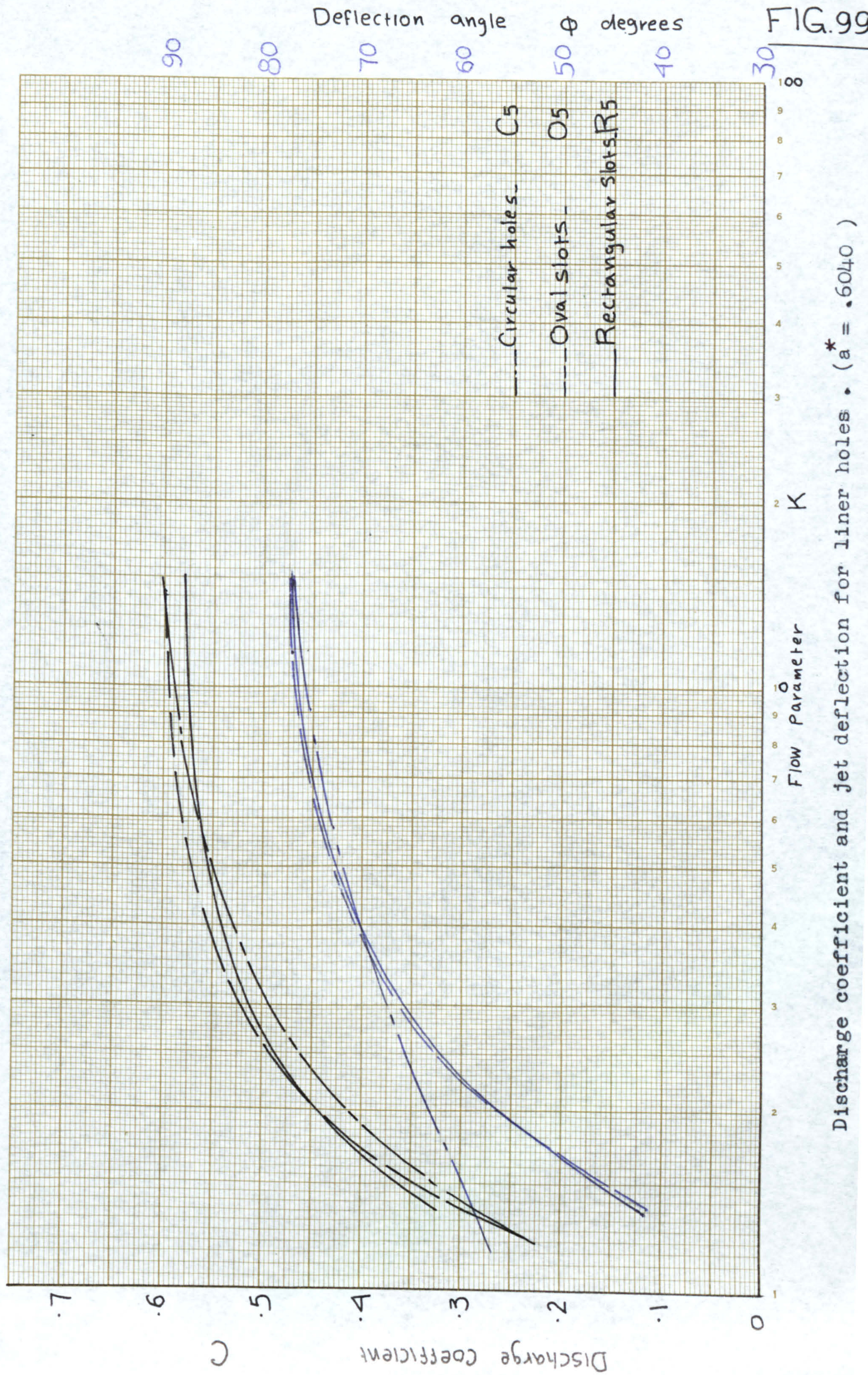
Discharge coefficient and jet deflection for liner holes. ($a^* = .1220$)

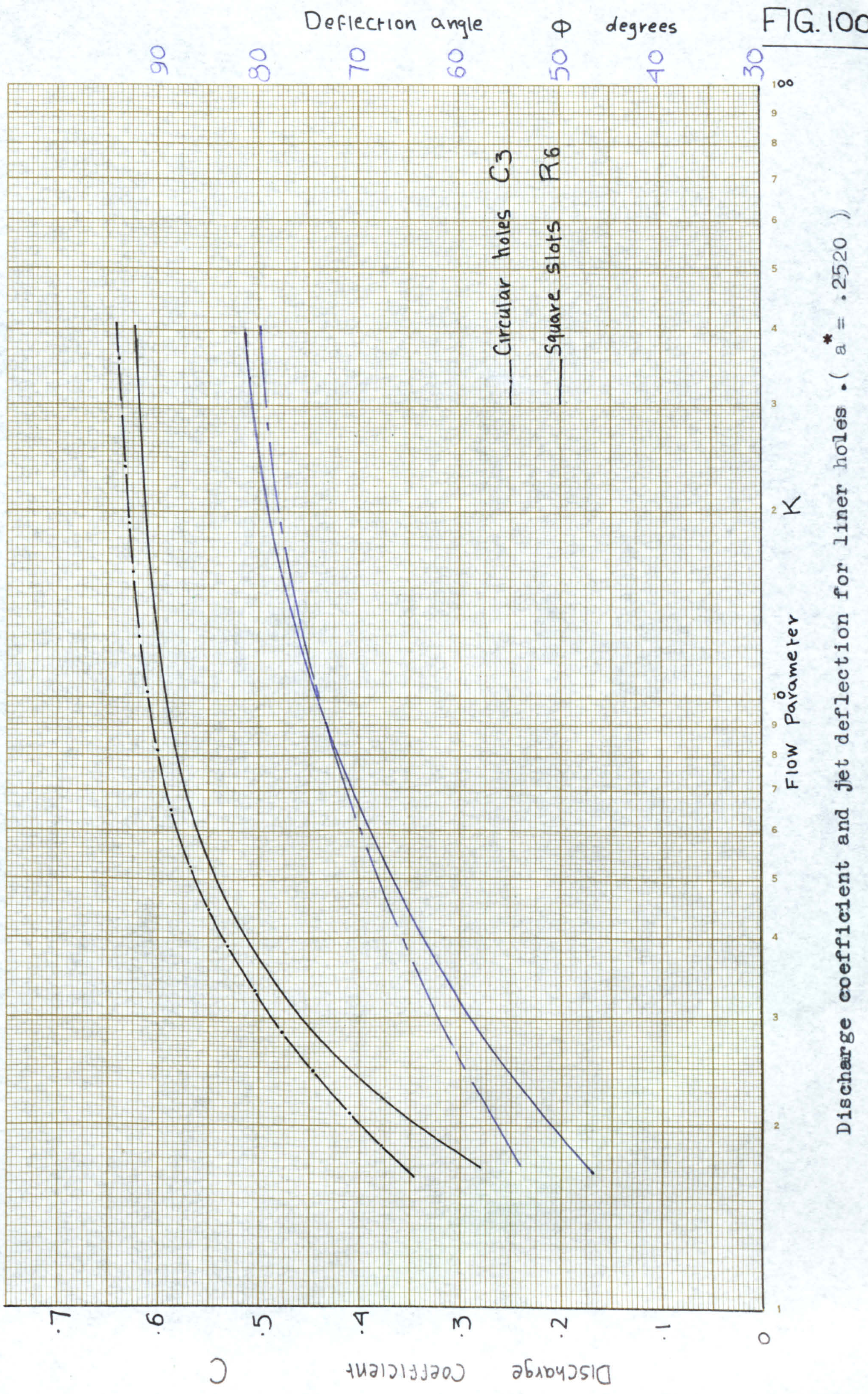


Discharge coefficient and jet deflection for liner holes • ($a^* = 0.2520$)

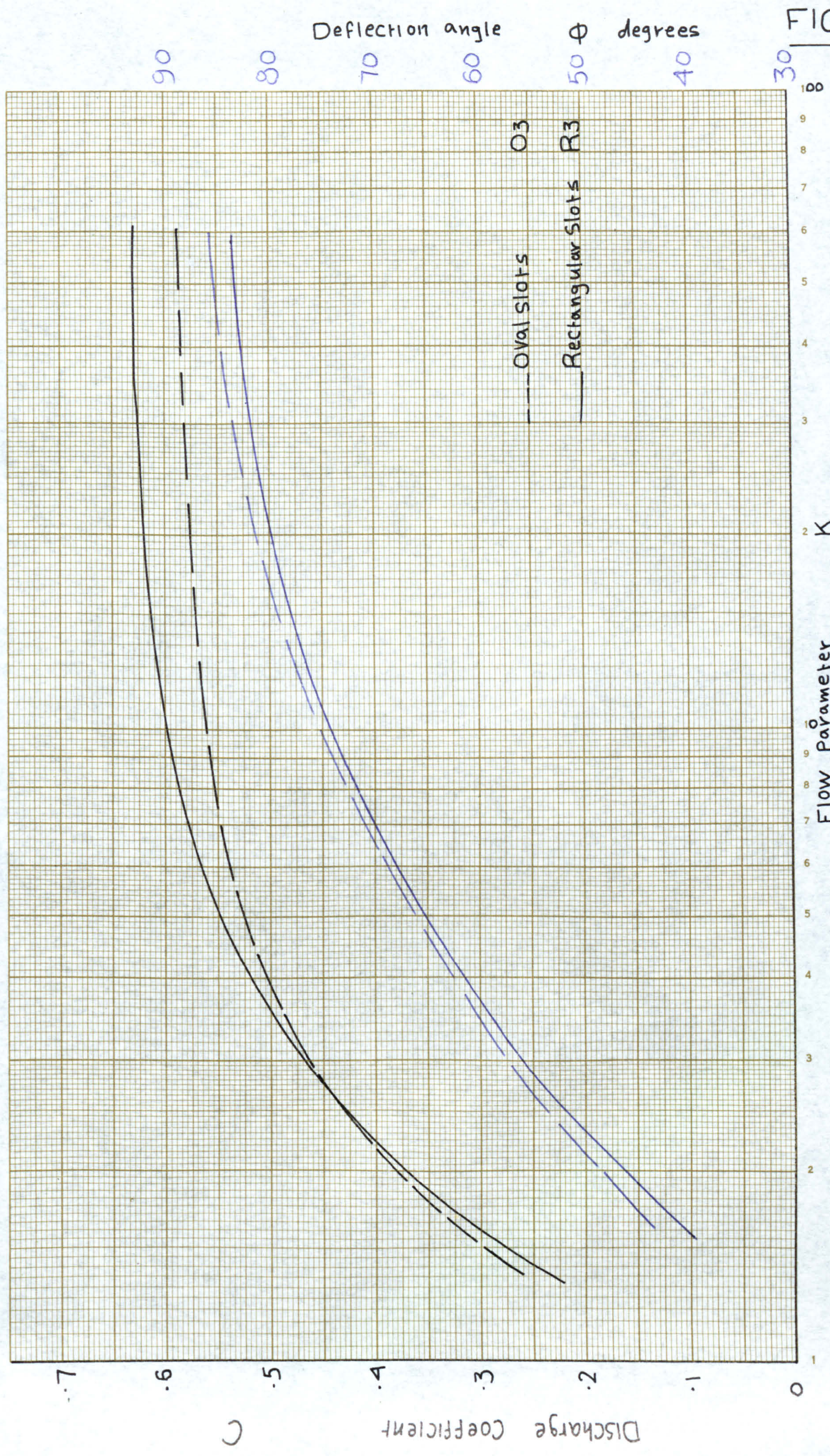


Discharge coefficient and jet deflection for liner holes. ($a^* = 0.3840$)





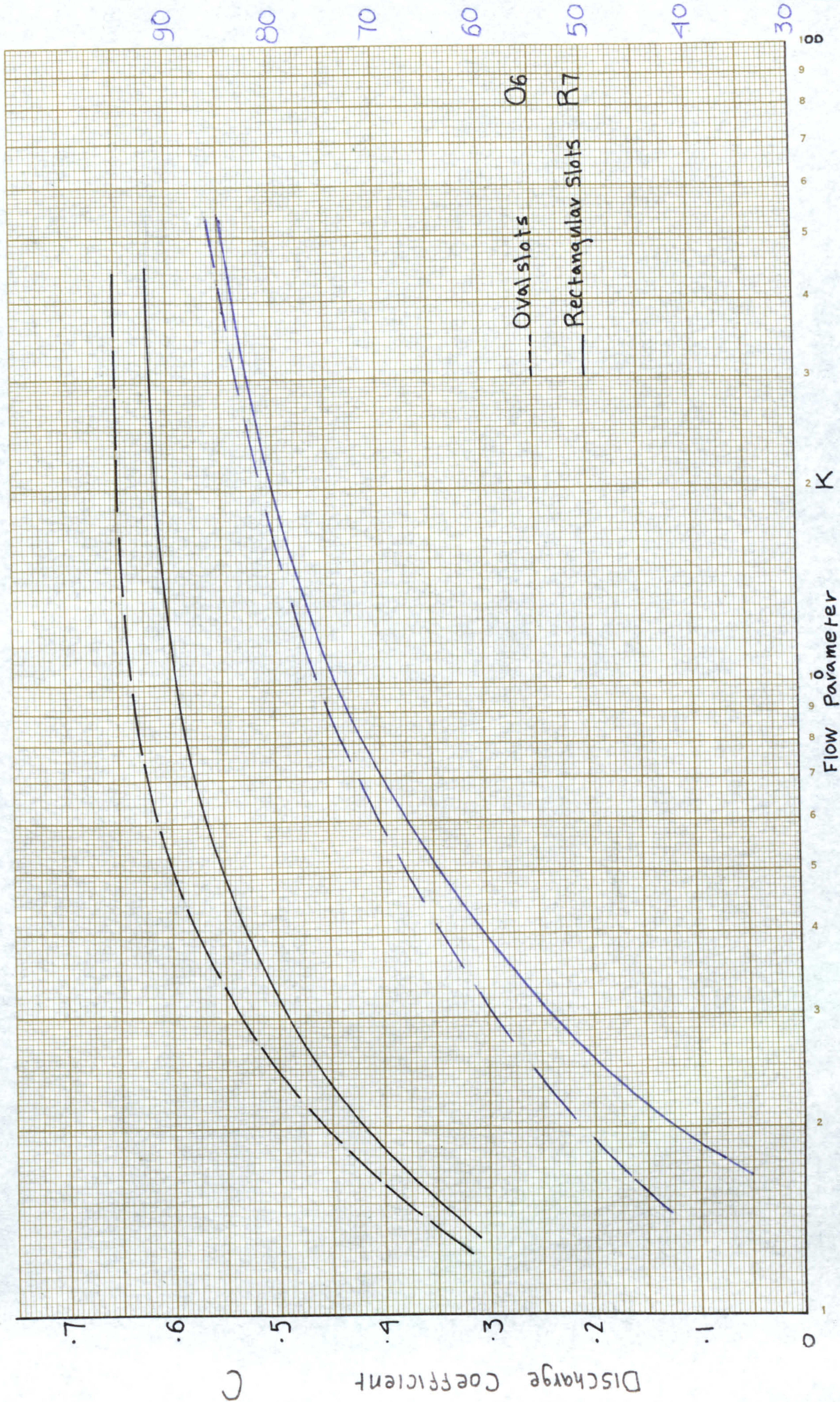
Discharge coefficient and jet deflection for liner holes. ($a^* = .2520$)



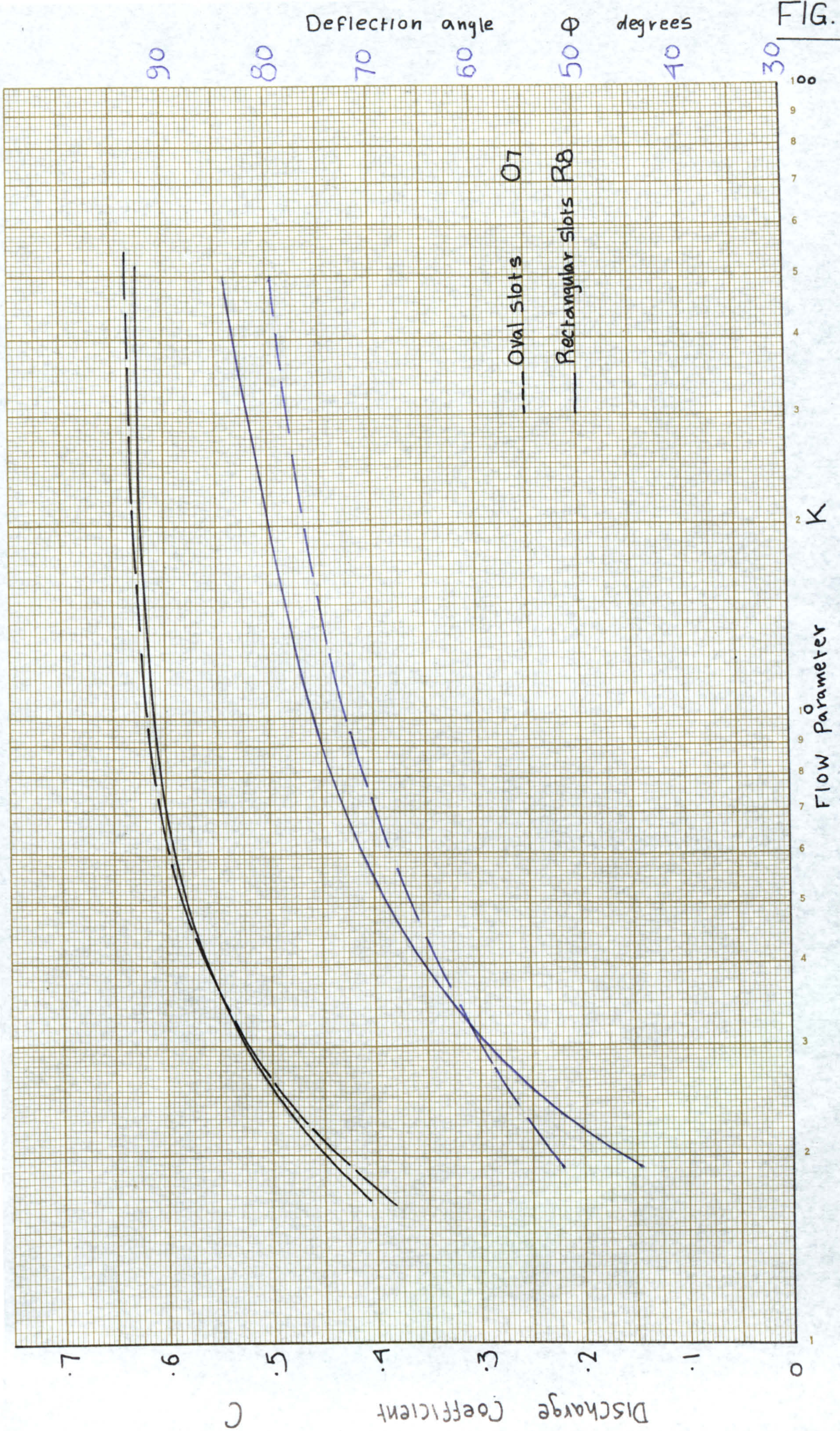
Discharge coefficient and jet deflection for liner holes. ($a^* = .2520$, Aspect ratio = 2.0)

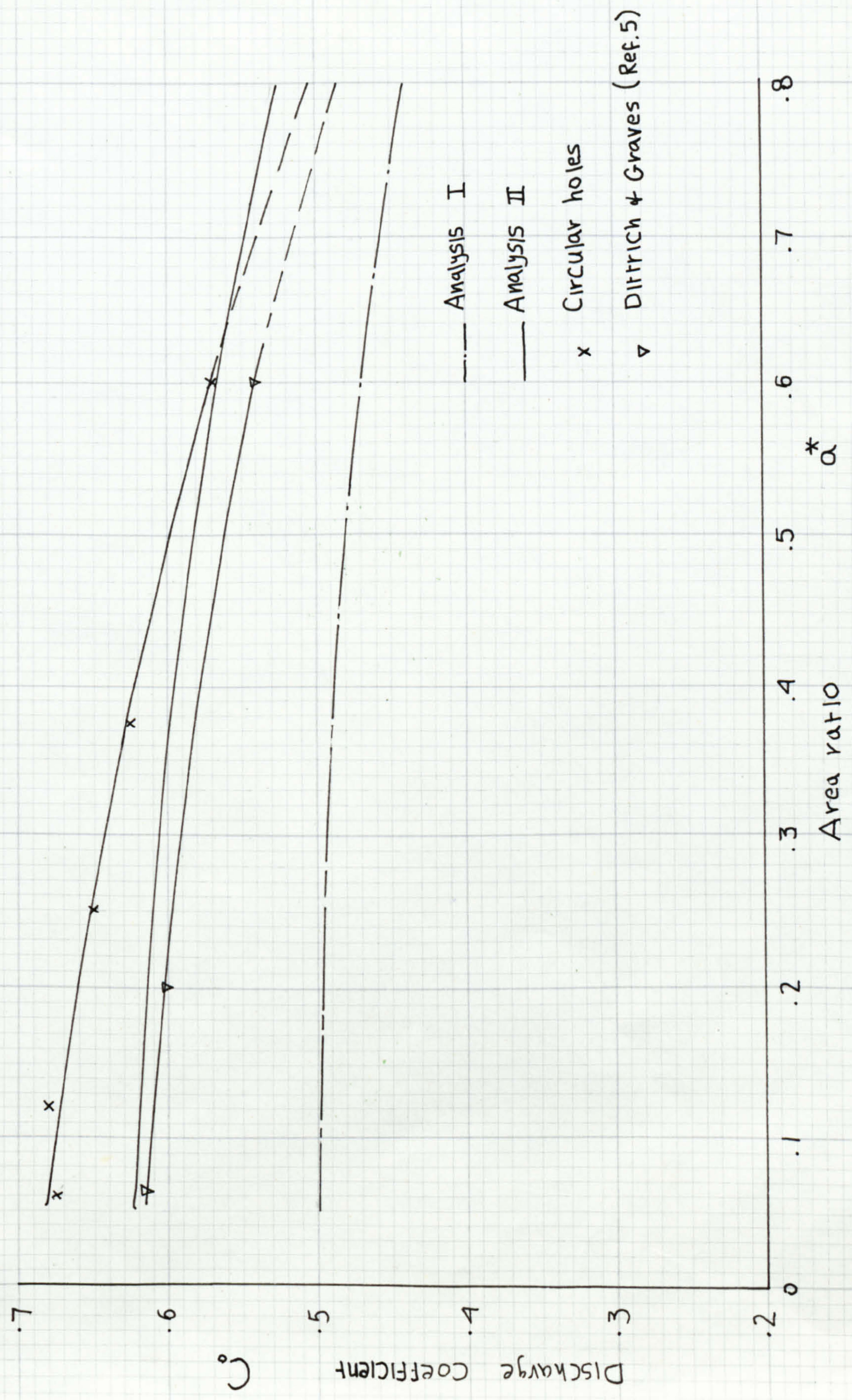
Deflection angle ϕ degrees

FIG. 102

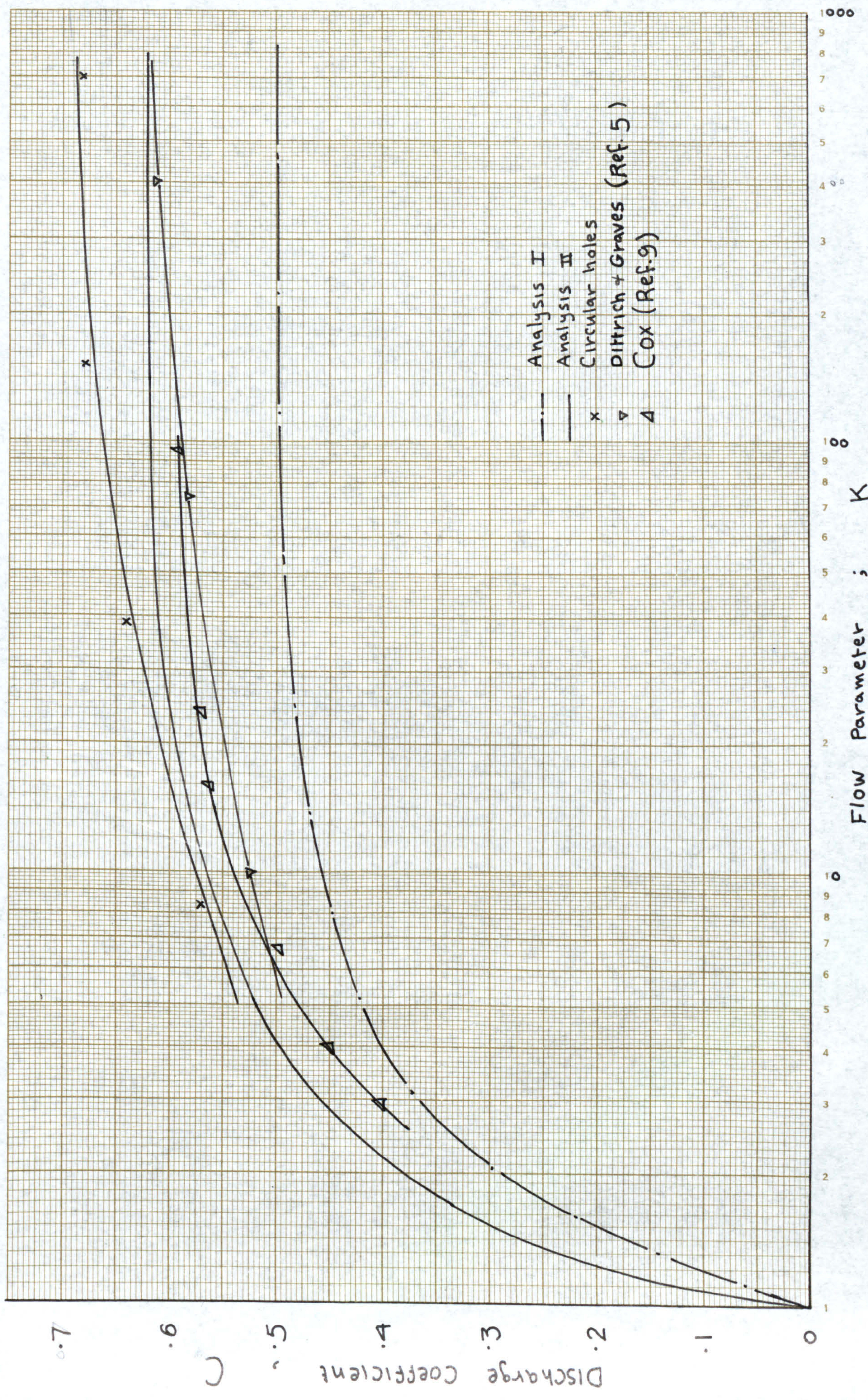


Discharge coefficient and jet deflection for liner holes. ($a^* = 0.2520$, Aspect ratio = 4.0)

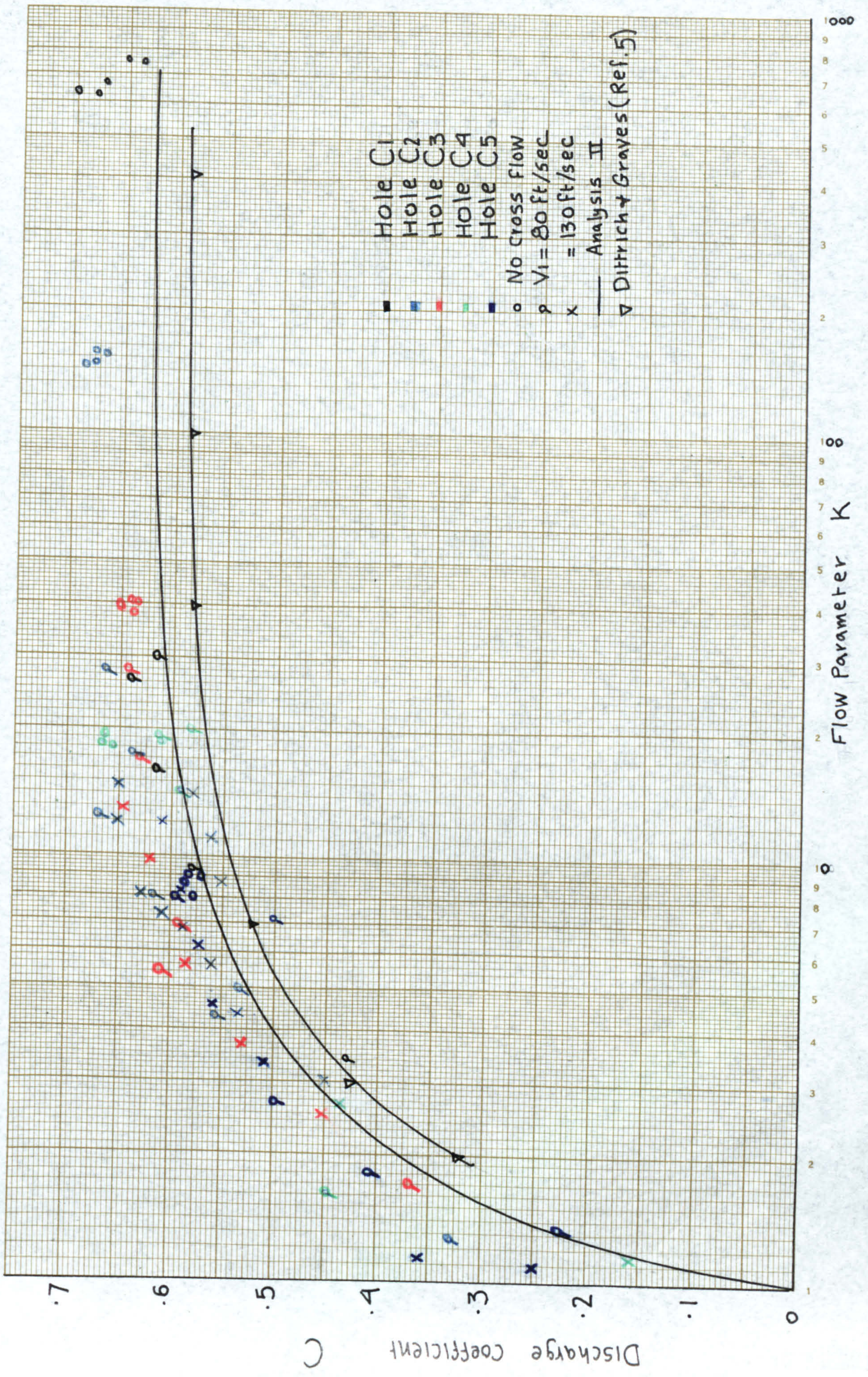




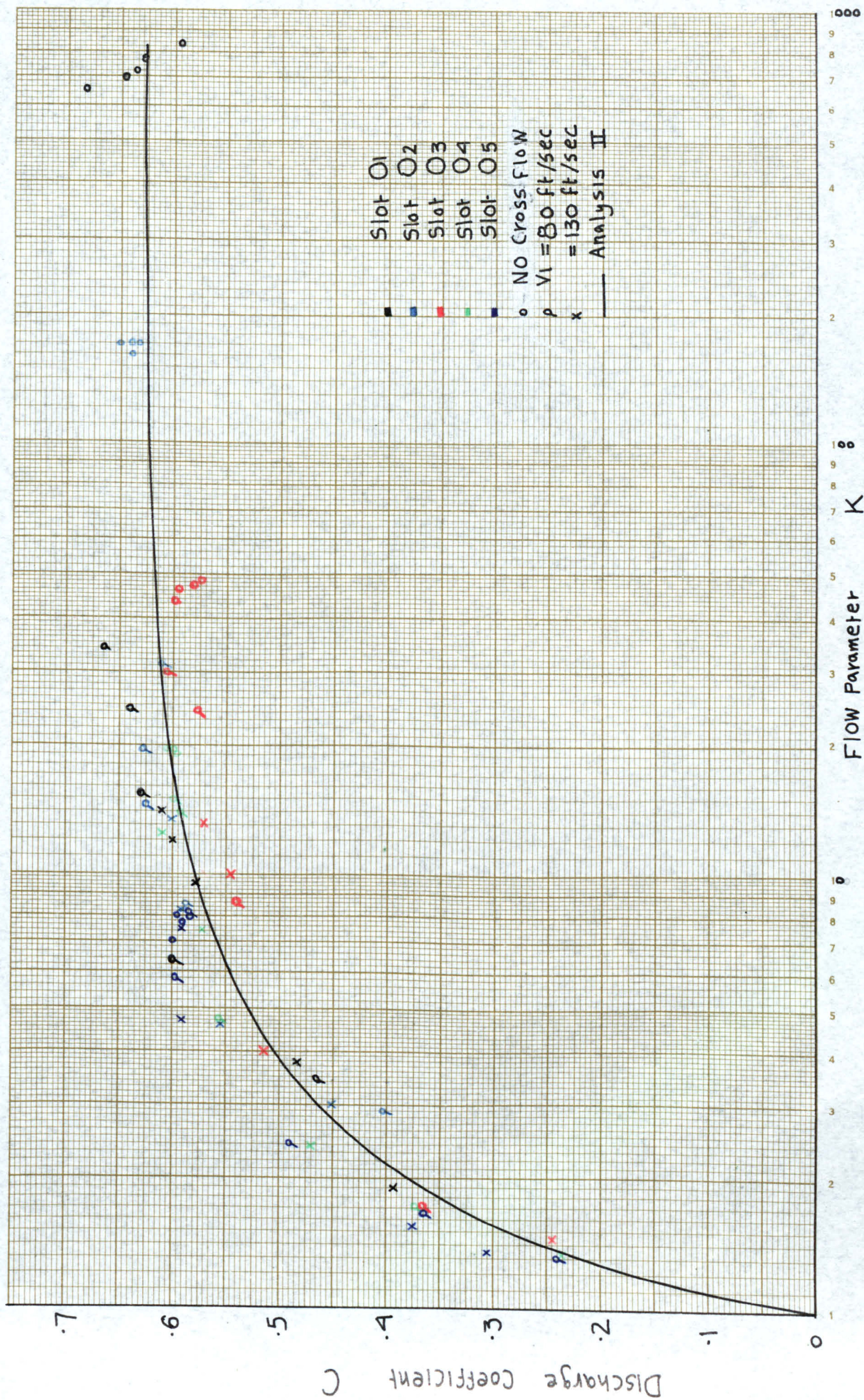
Variation of discharge coefficient with area ratio - No cross flow.



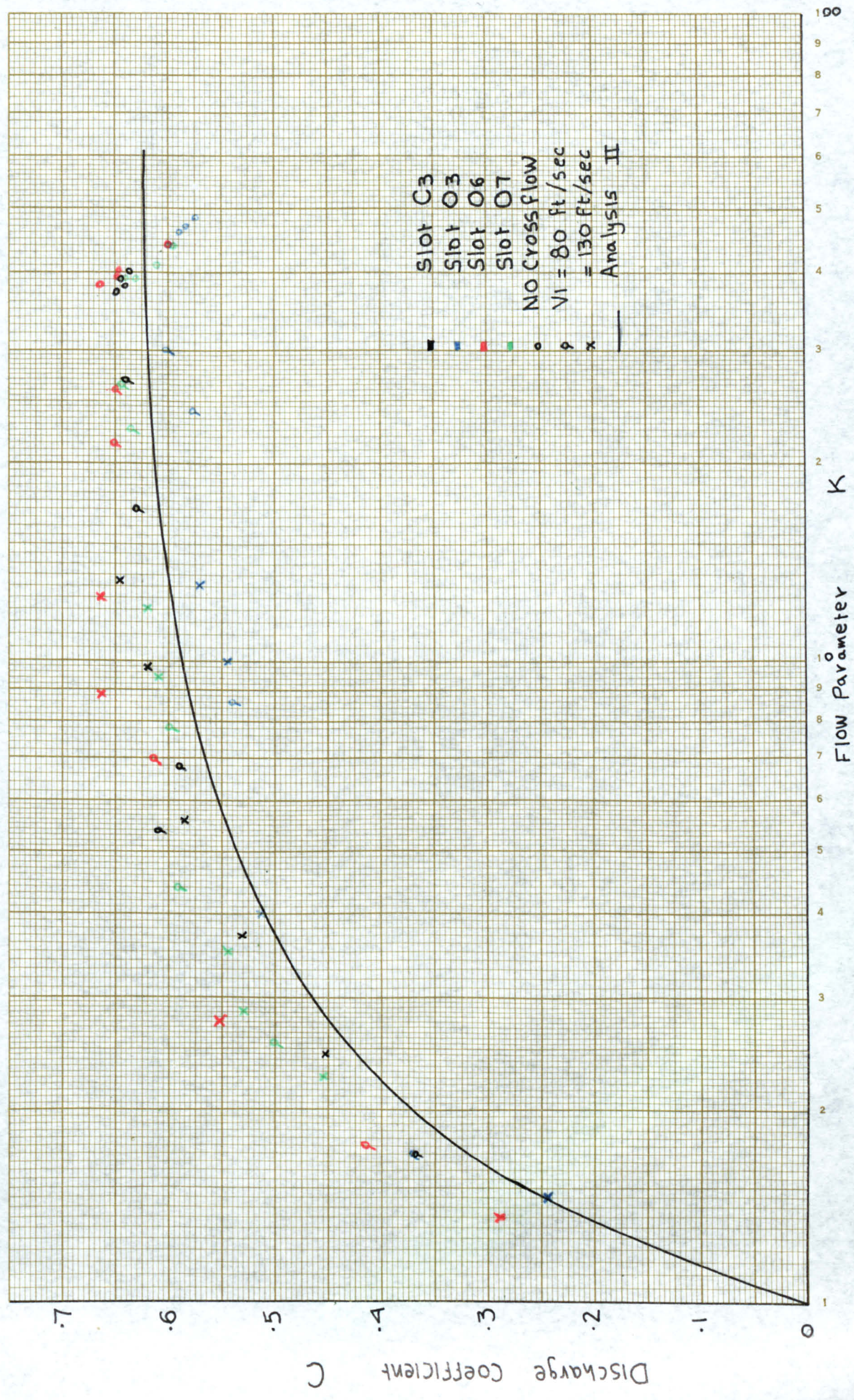
Variation of discharge coefficient with flow parameter. (comparison of results)



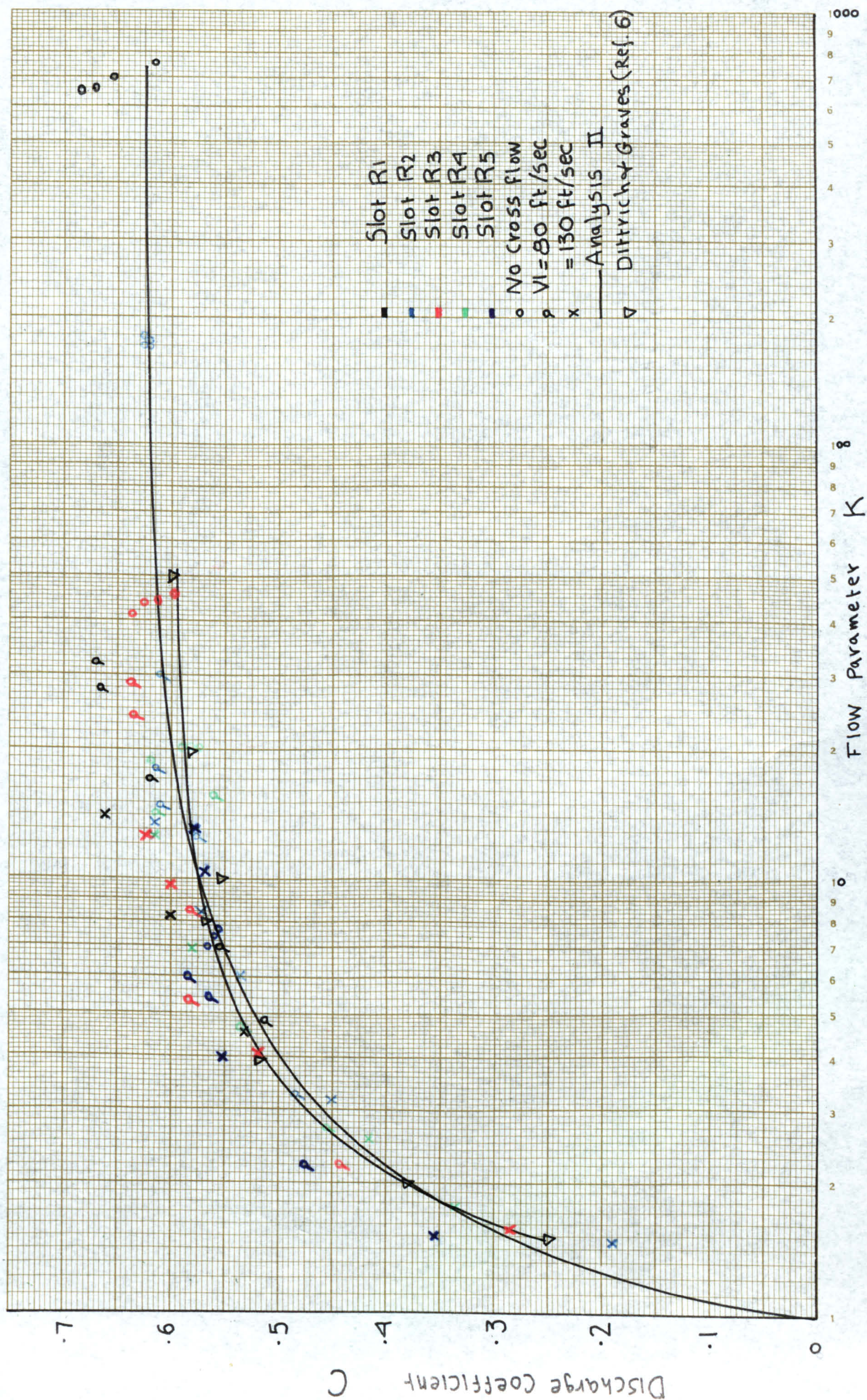
Discharge coefficient for circular holes . (comparison of results)



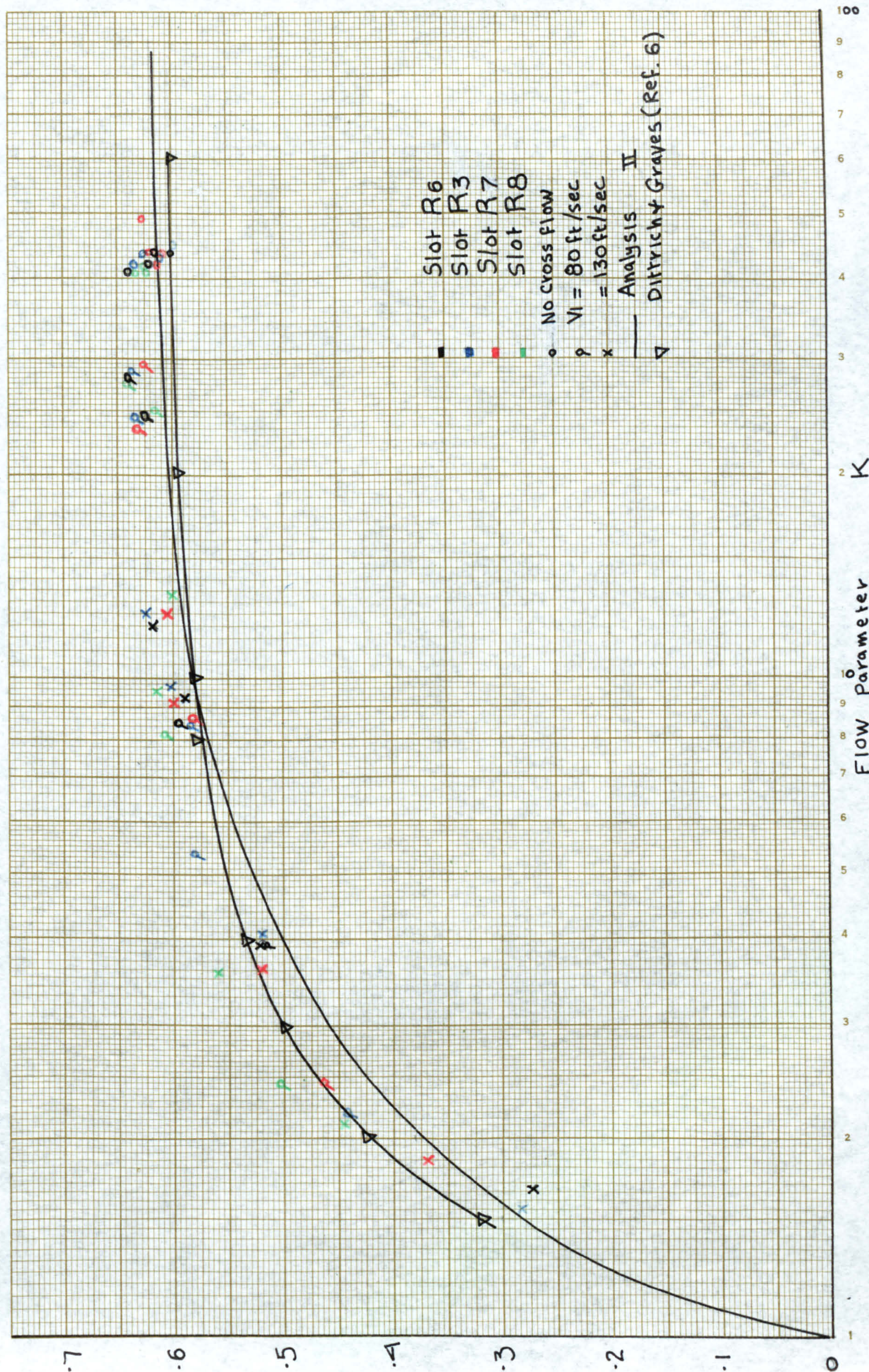
Discharge coefficient for oval slots • (comparison of results)



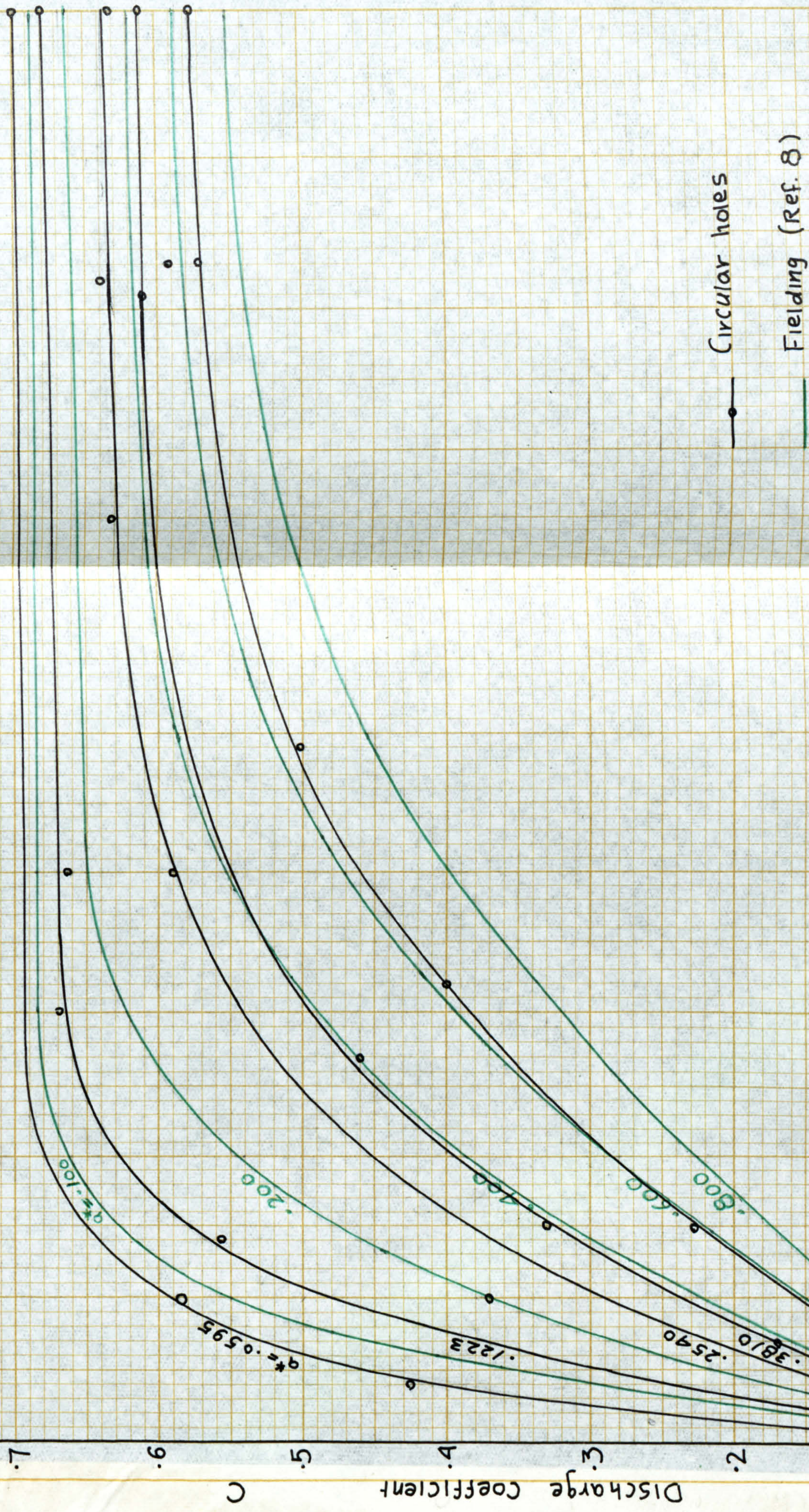
Discharge coefficient for oval slots - $a^* = 0.2520$. (comparison of results)

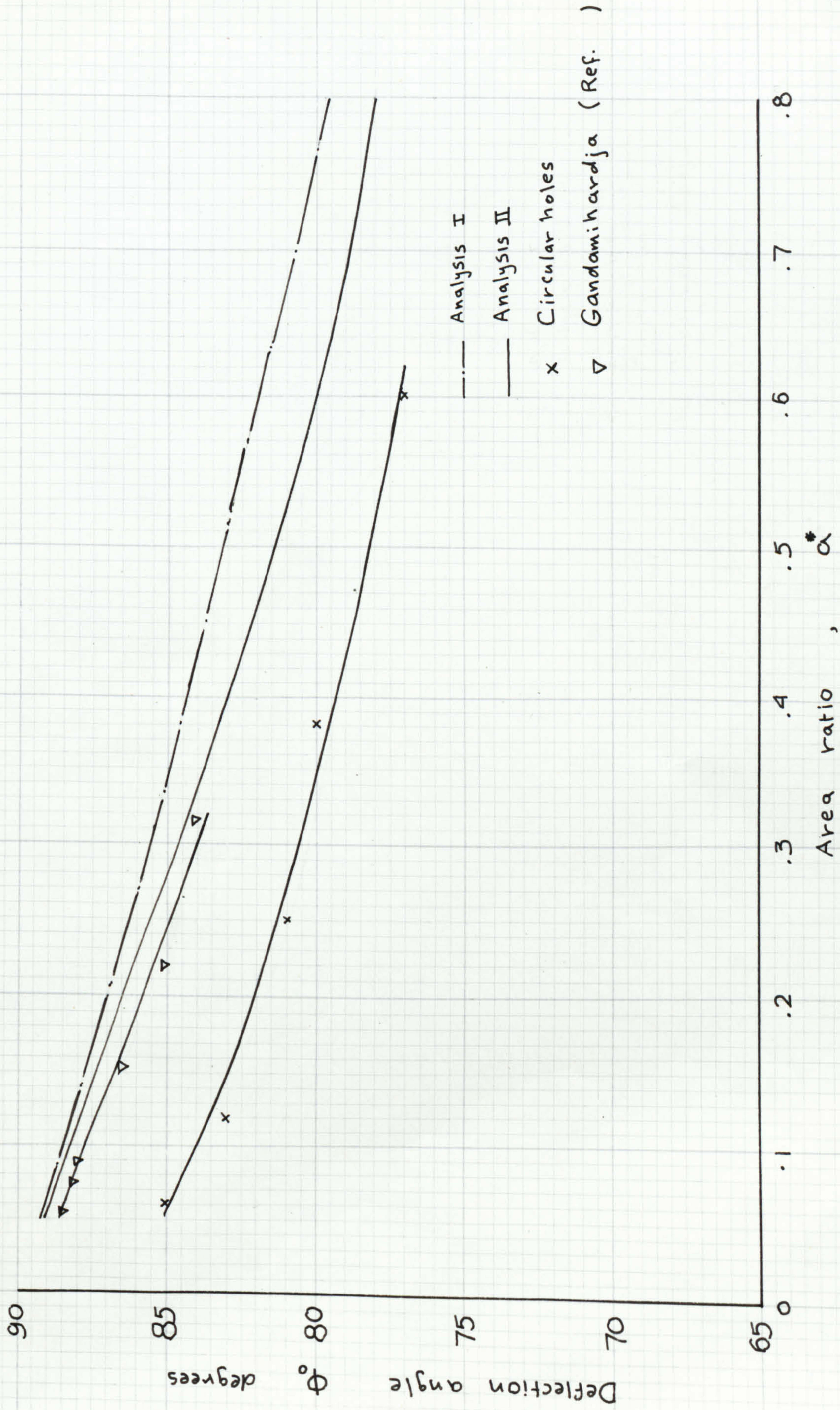


Discharge coefficient for rectangular slots-Aspect ratio =2.0. (comparison of results)

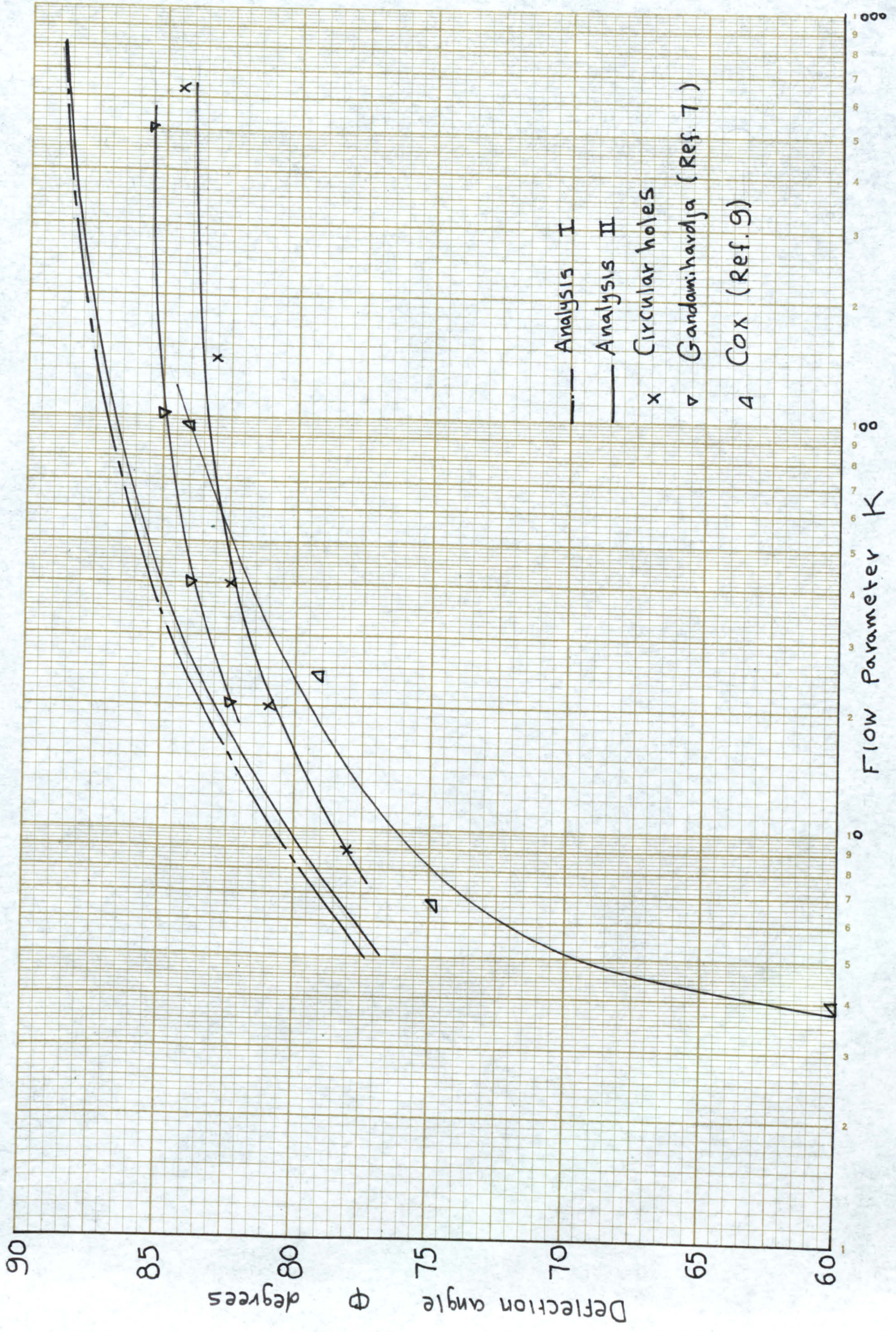


Discharge coefficient for rectangular slots - $a^* = .2520$ (comparison of results)

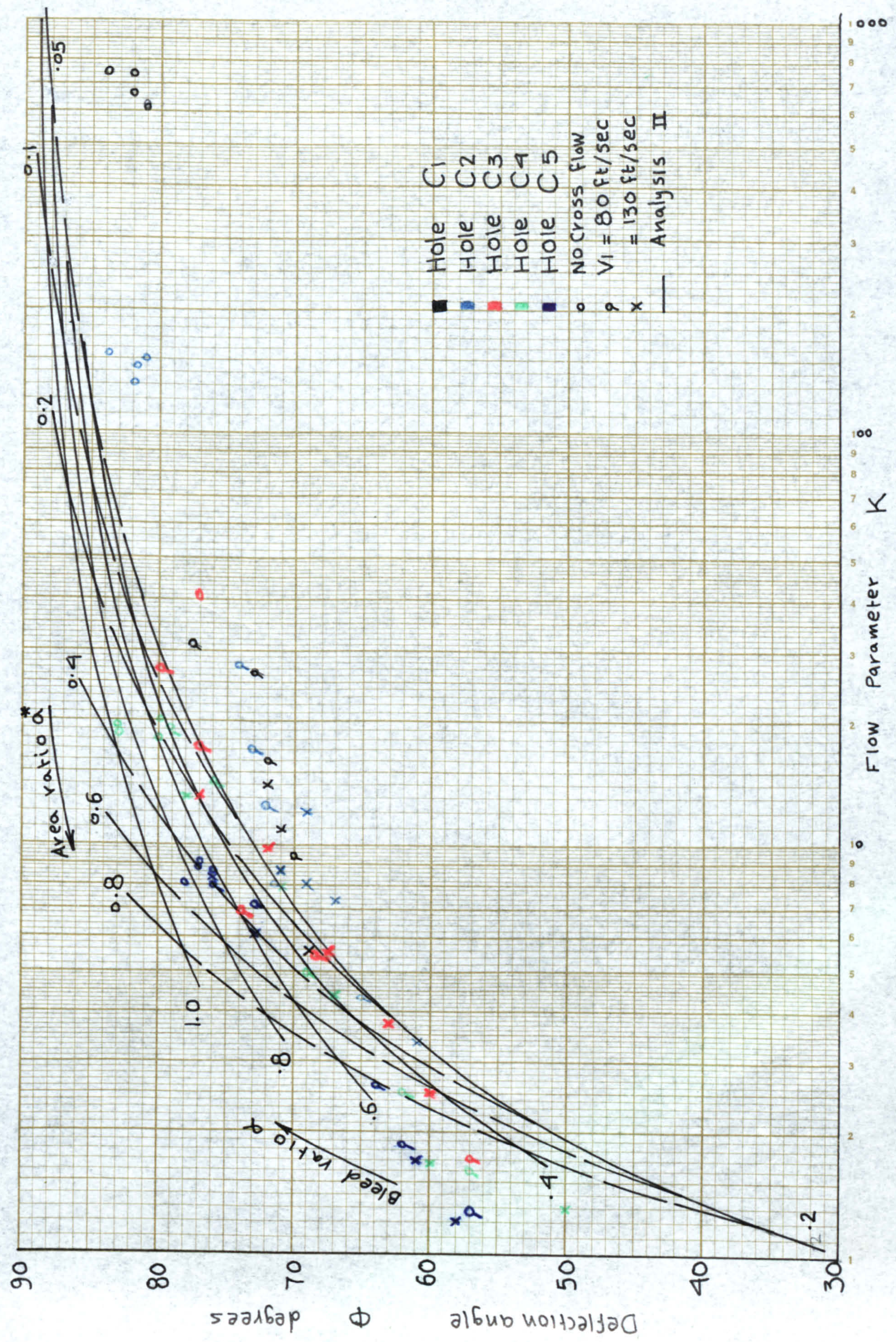




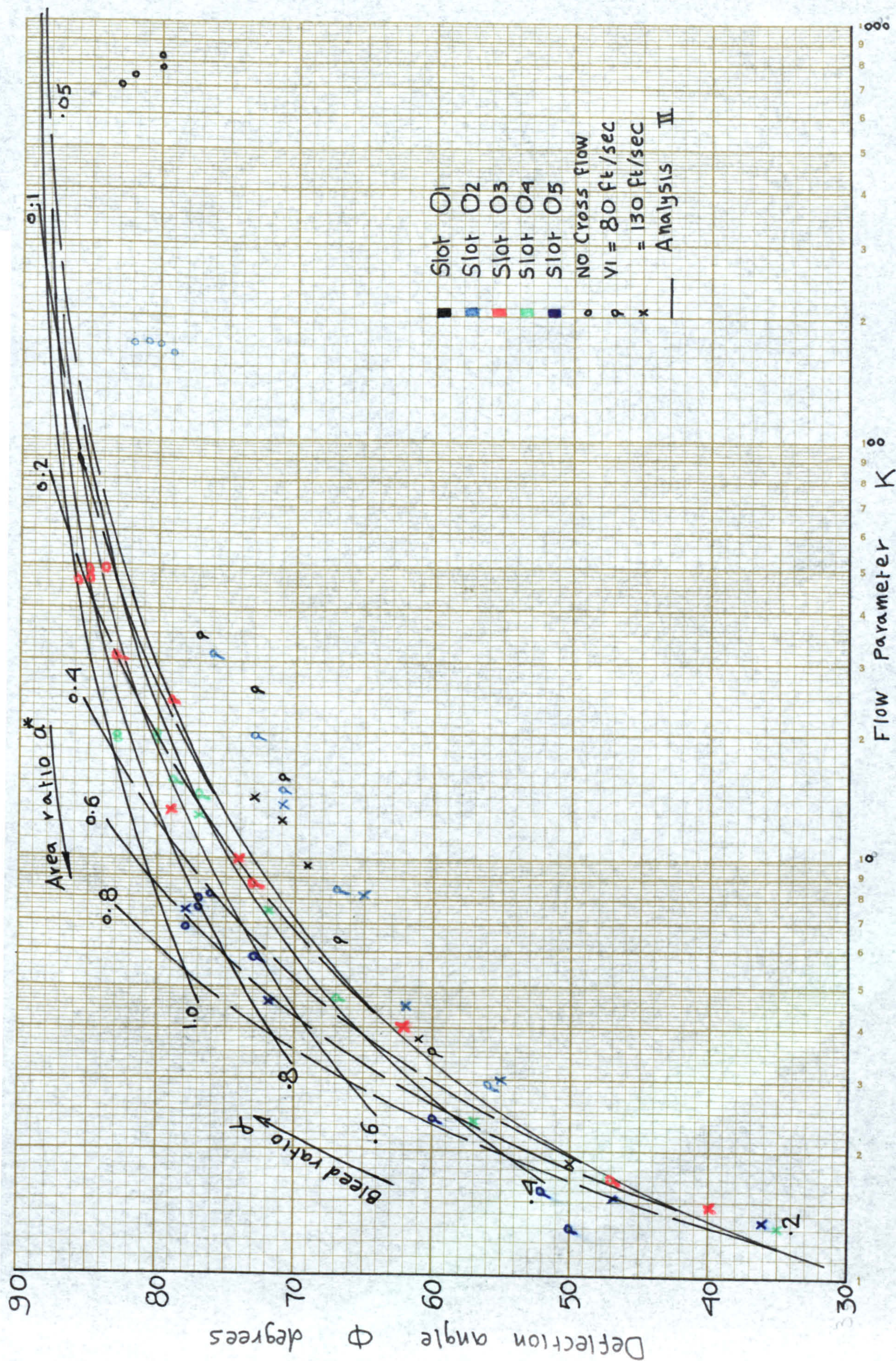
Jet deflection for circular holes . (comparison of results)



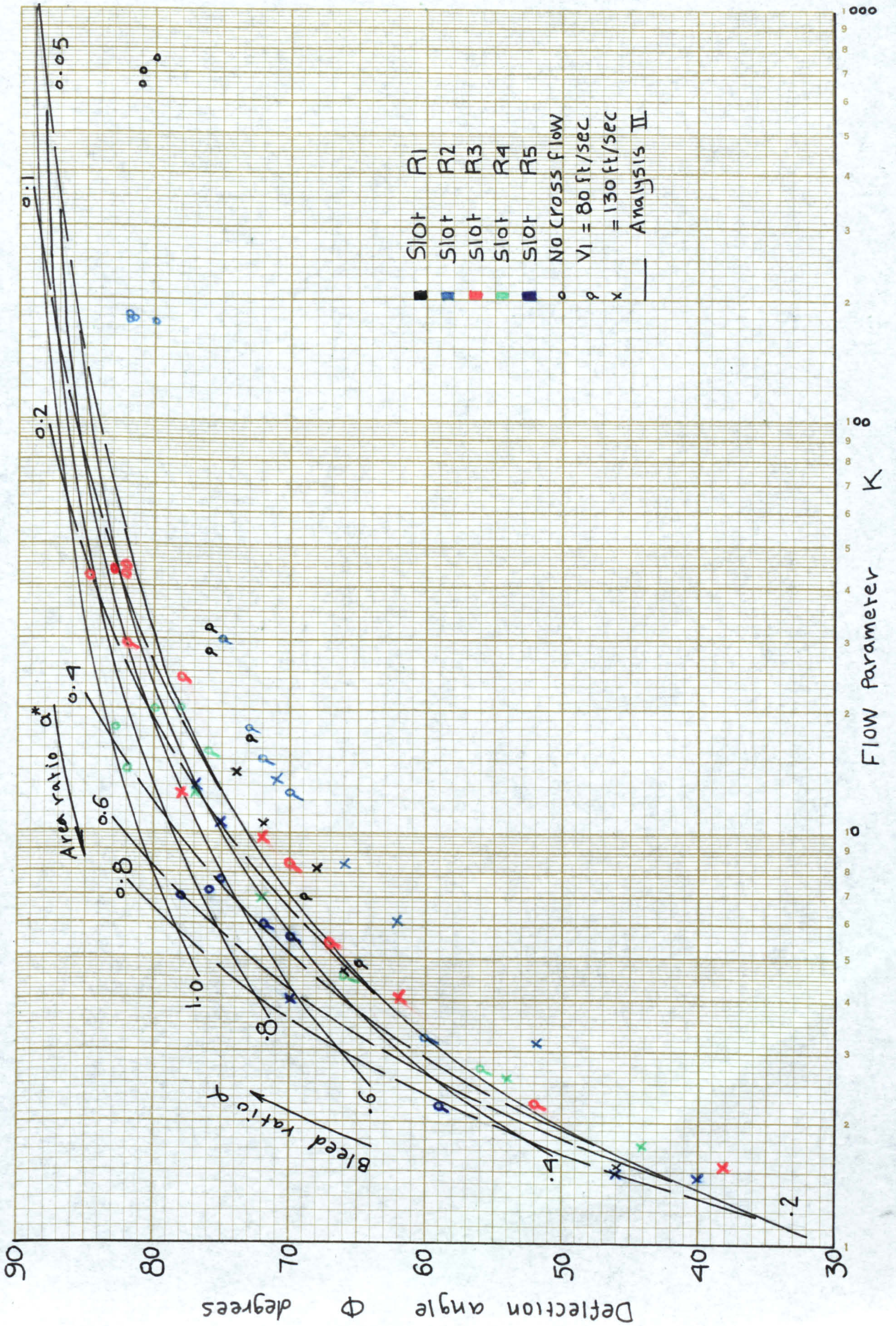
Jet deflection for liner holes . (comparison of results)



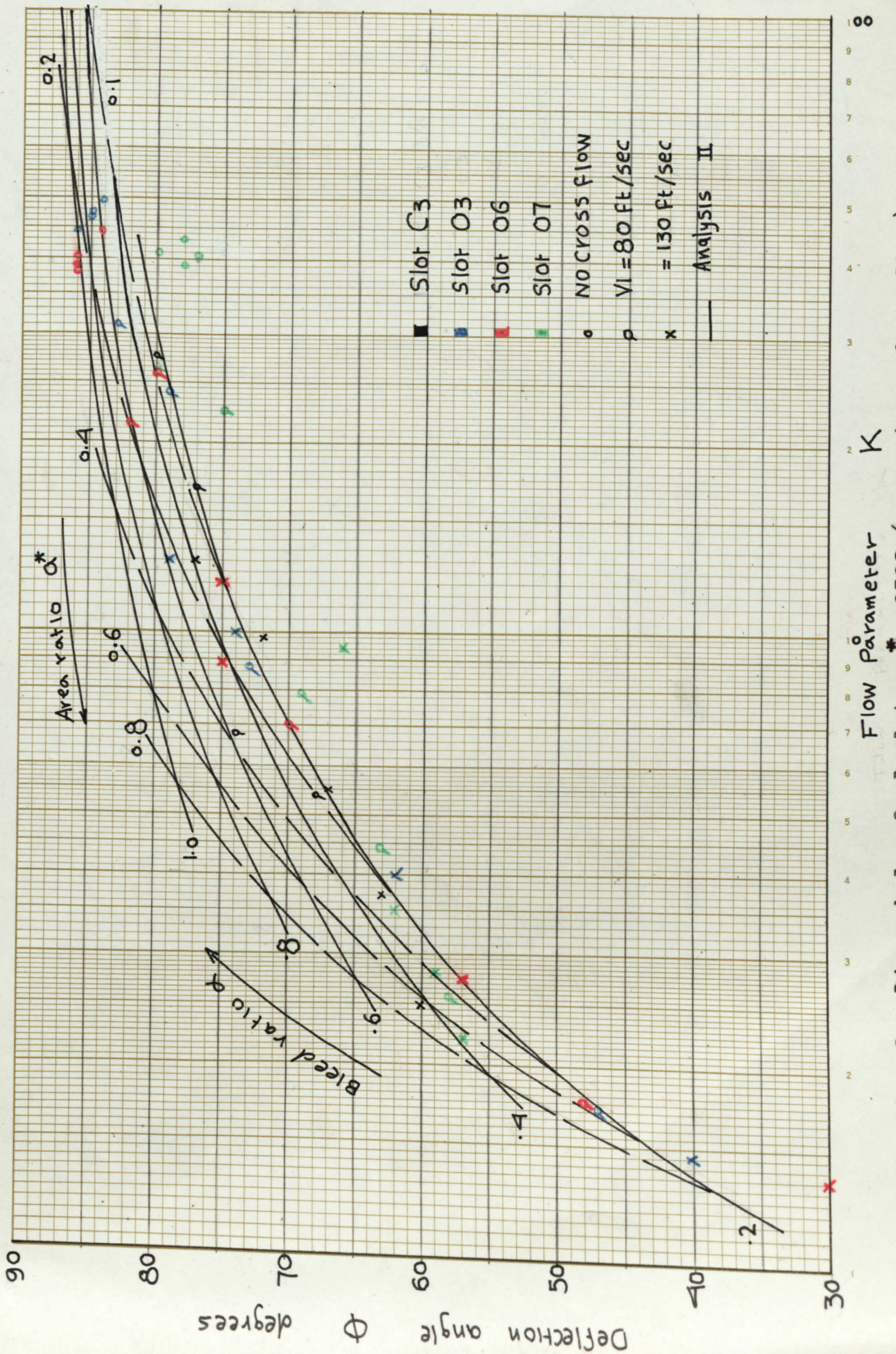
Jet deflection for circular liner holes. (comparison of results)



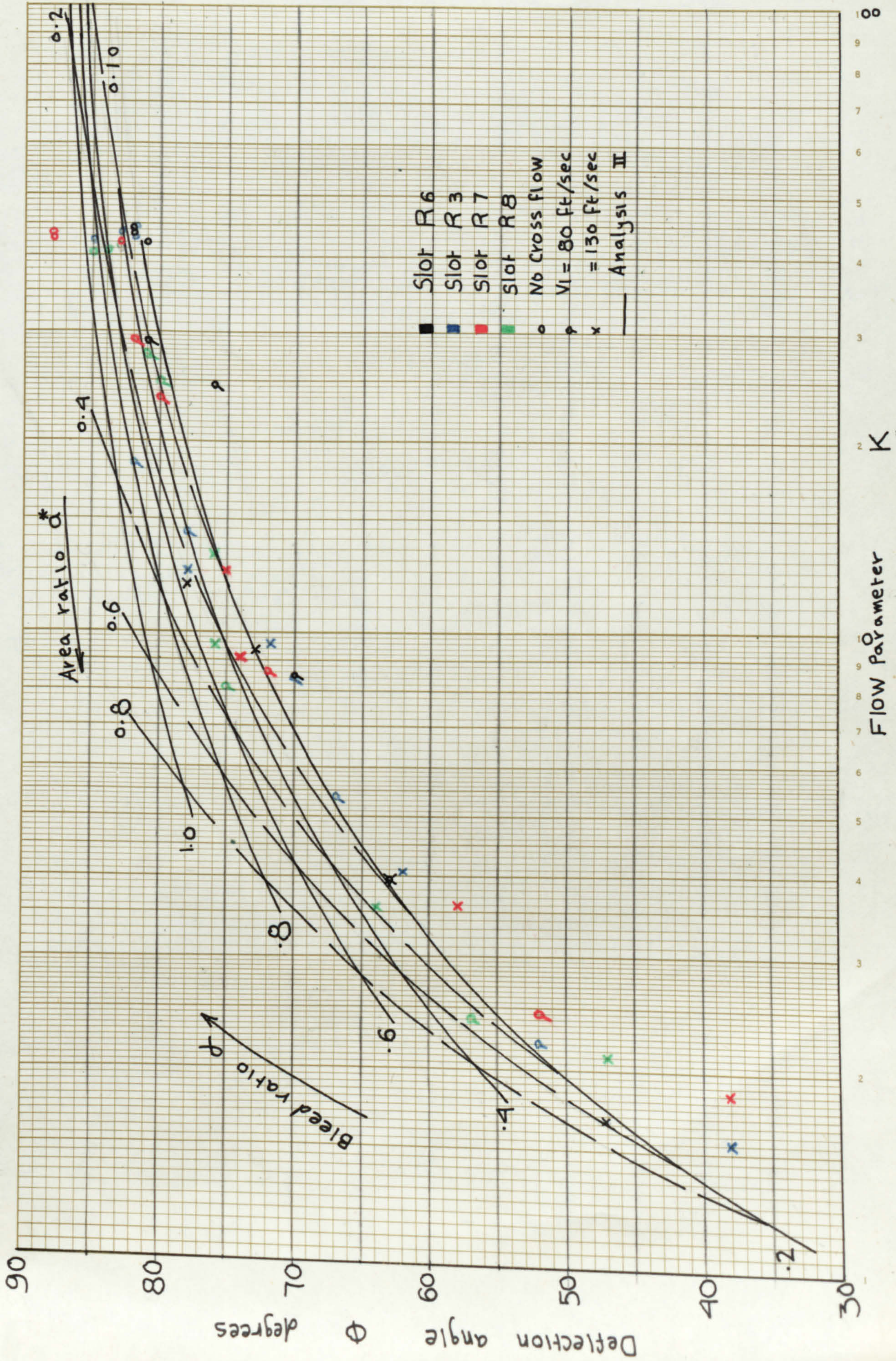
Jet deflection for liner holes -oval slots, Aspect ratio = 2.0. (comparison of results)



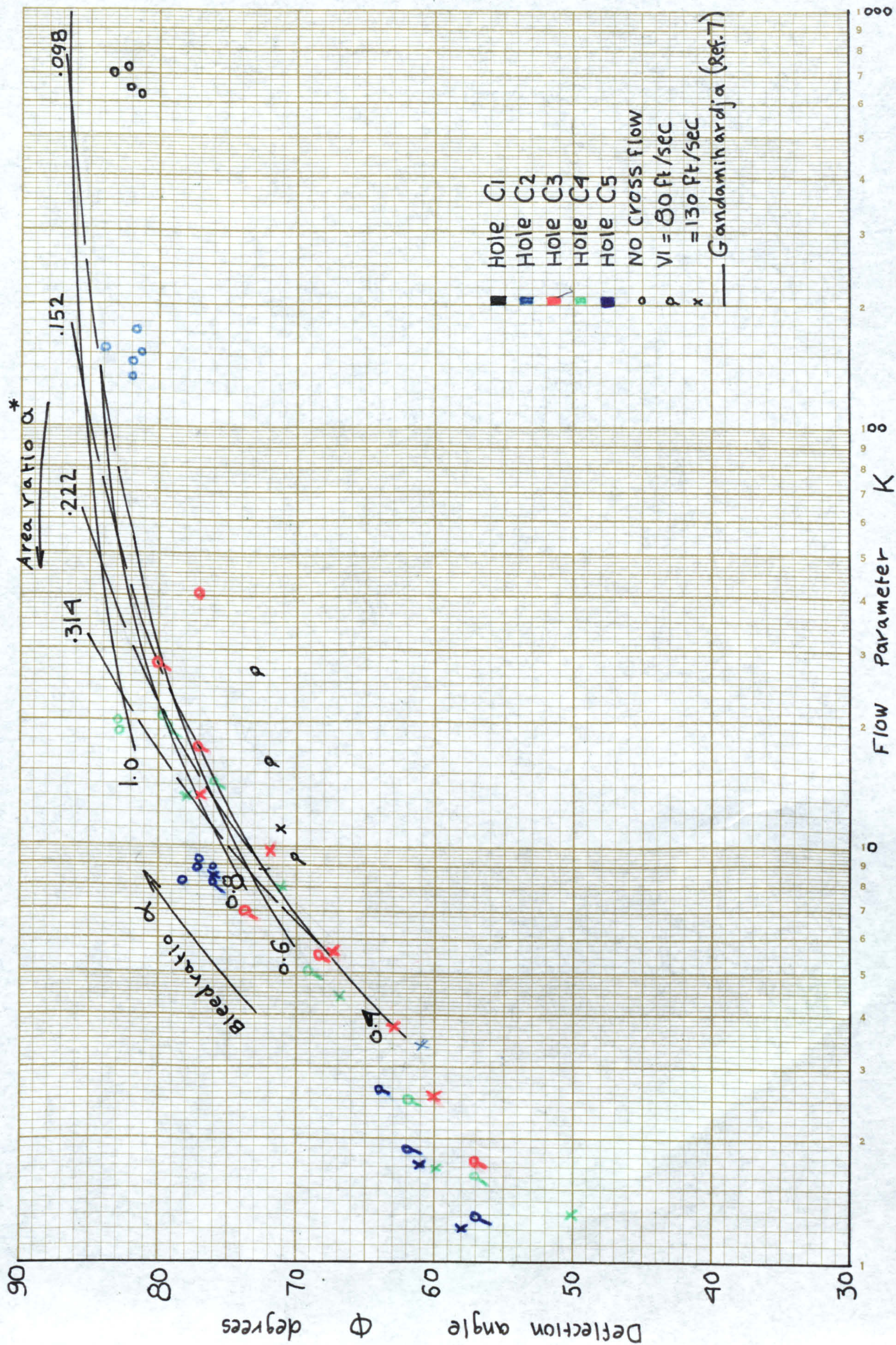
Jet deflection for liner holes -Rectangular slots, Aspect ratio=2.0 (comparison of results)



Jet deflection for liner holes-Oval slots, $a^* = 0.2520$ (comparison of results)

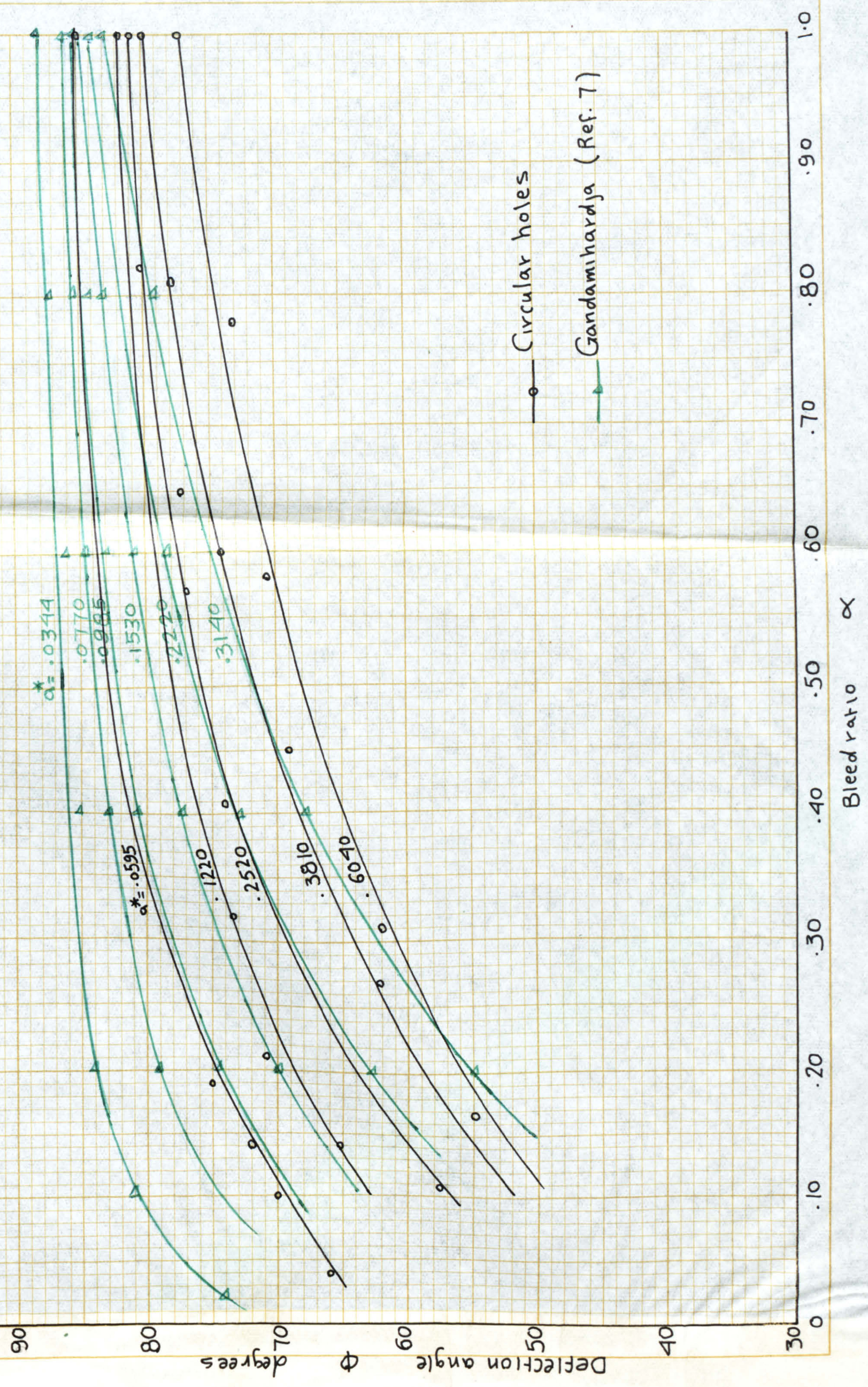


Jet deflection for liner holes-Rectangular slots, $a^* = .2520$ (comparison of results)

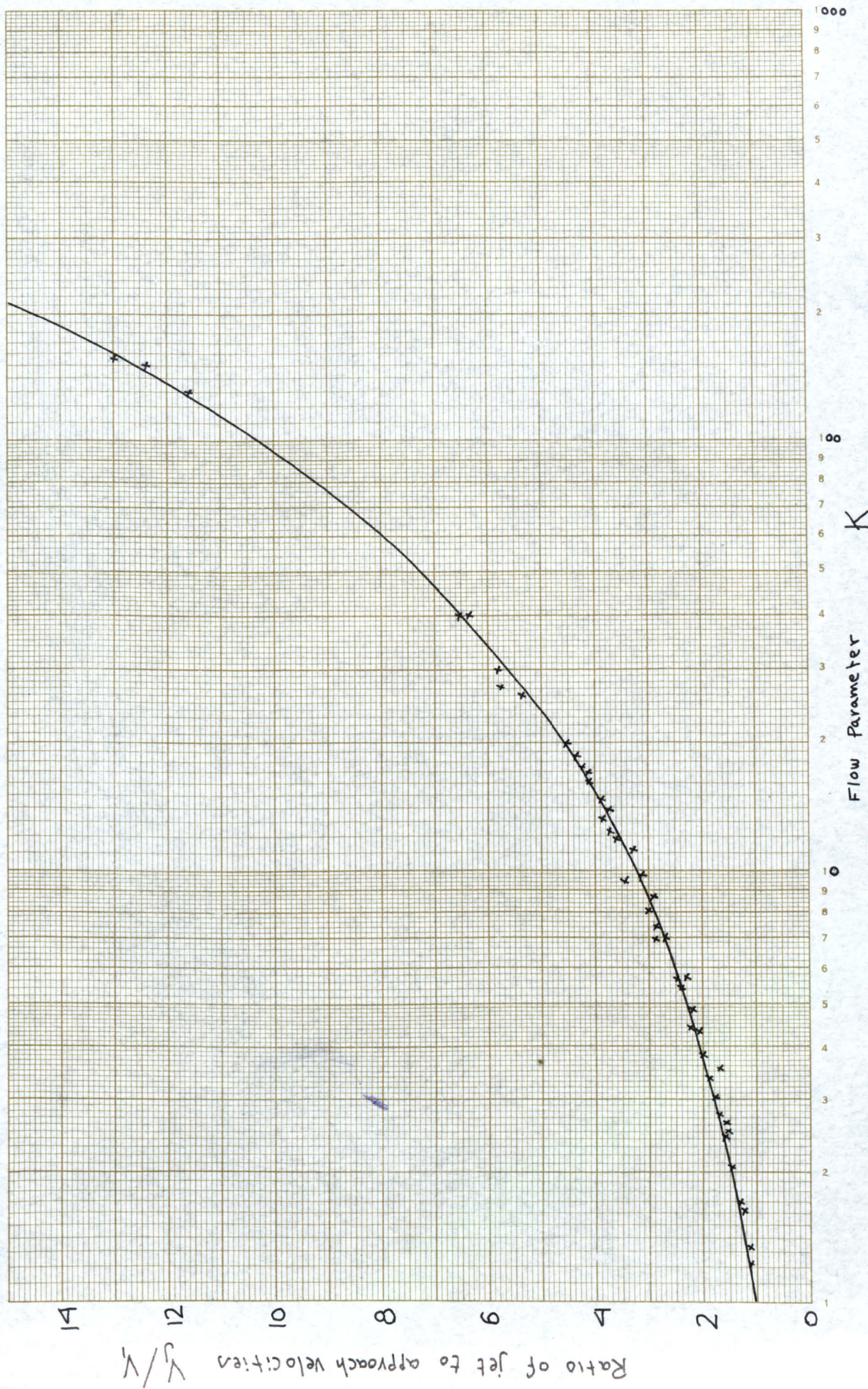


Jet deflection for circular holes. (comparison of results)

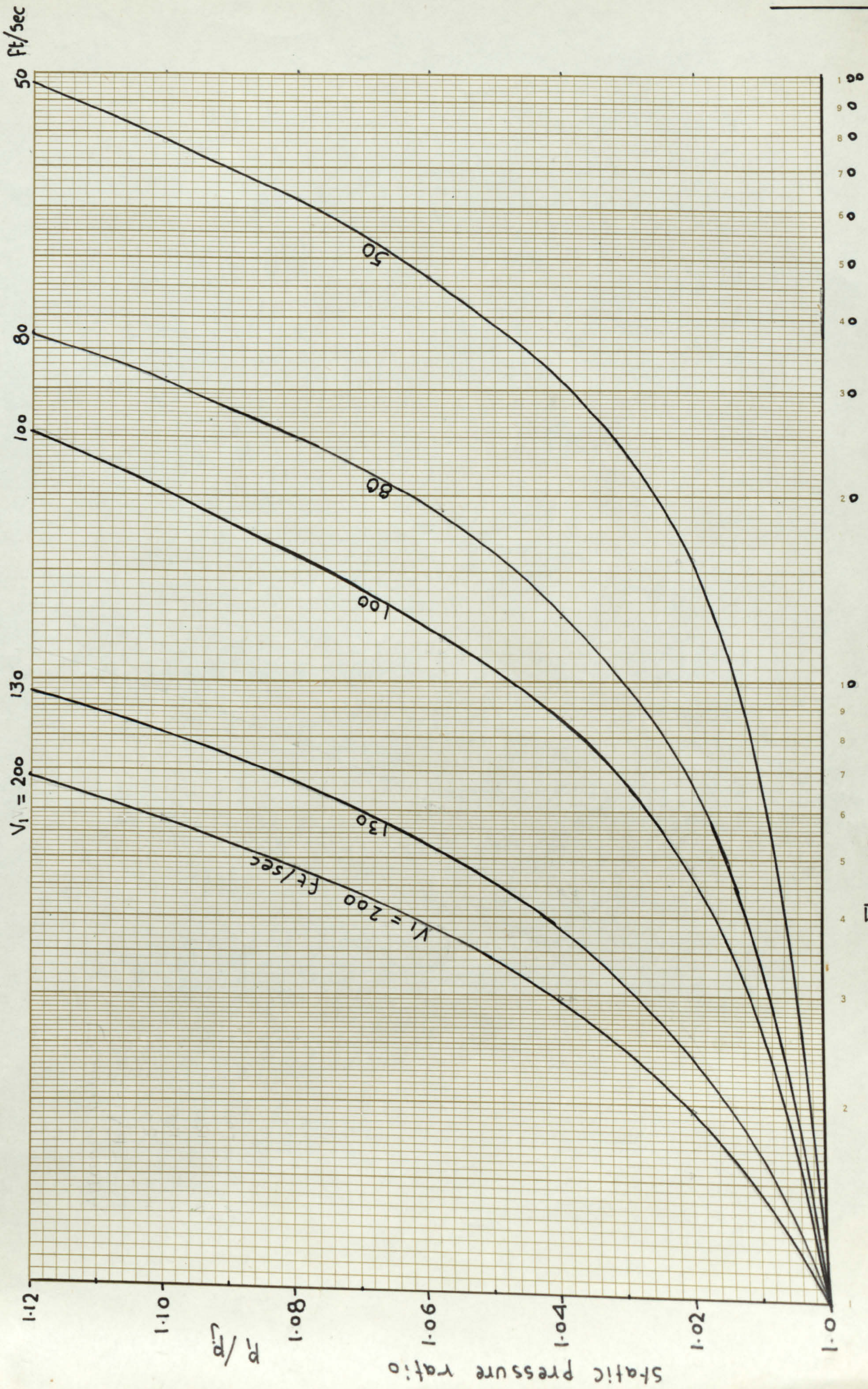
Jet deflection for circular liner holes. (comparison of results)



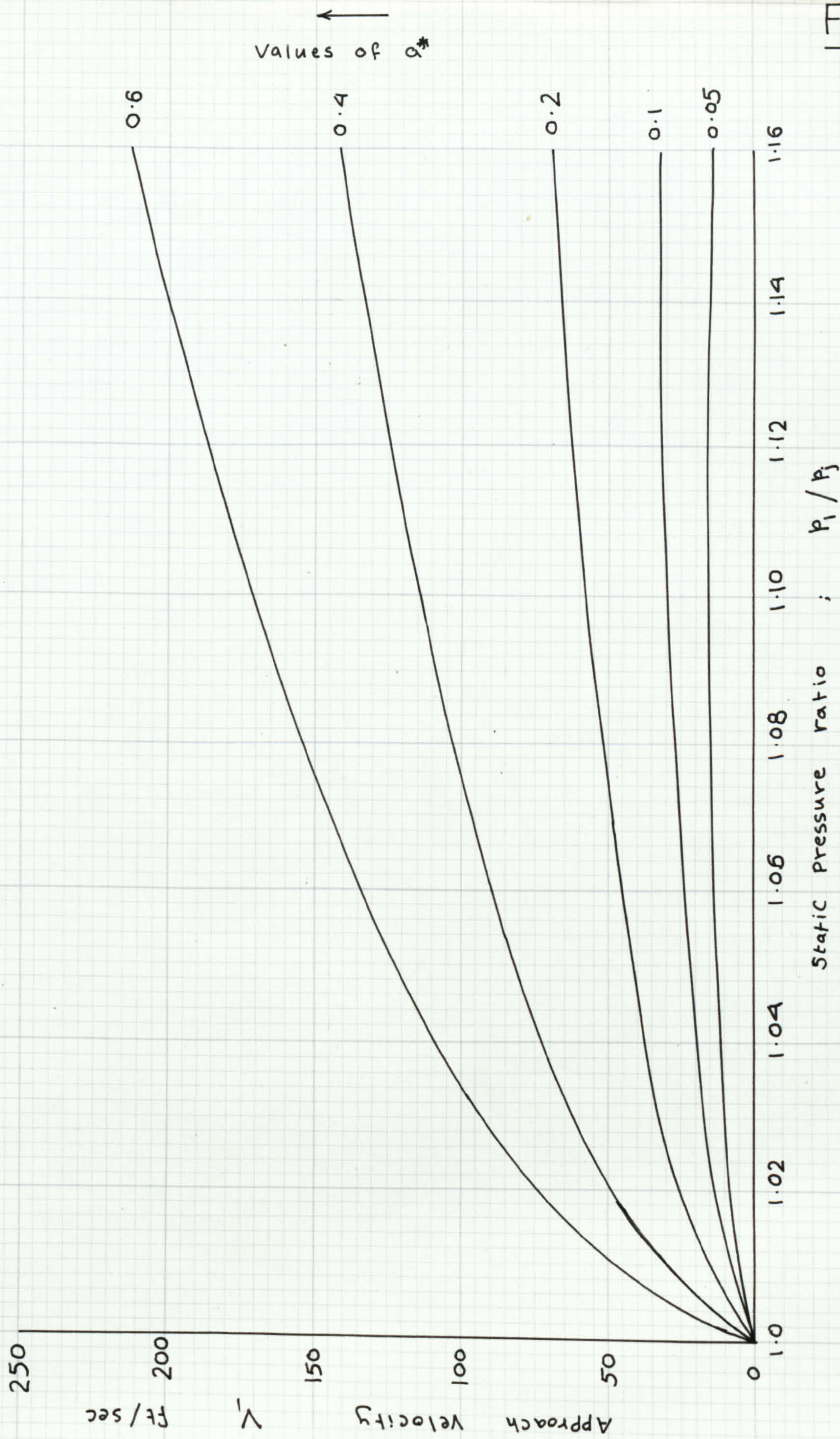
APPENDICES FIGURES



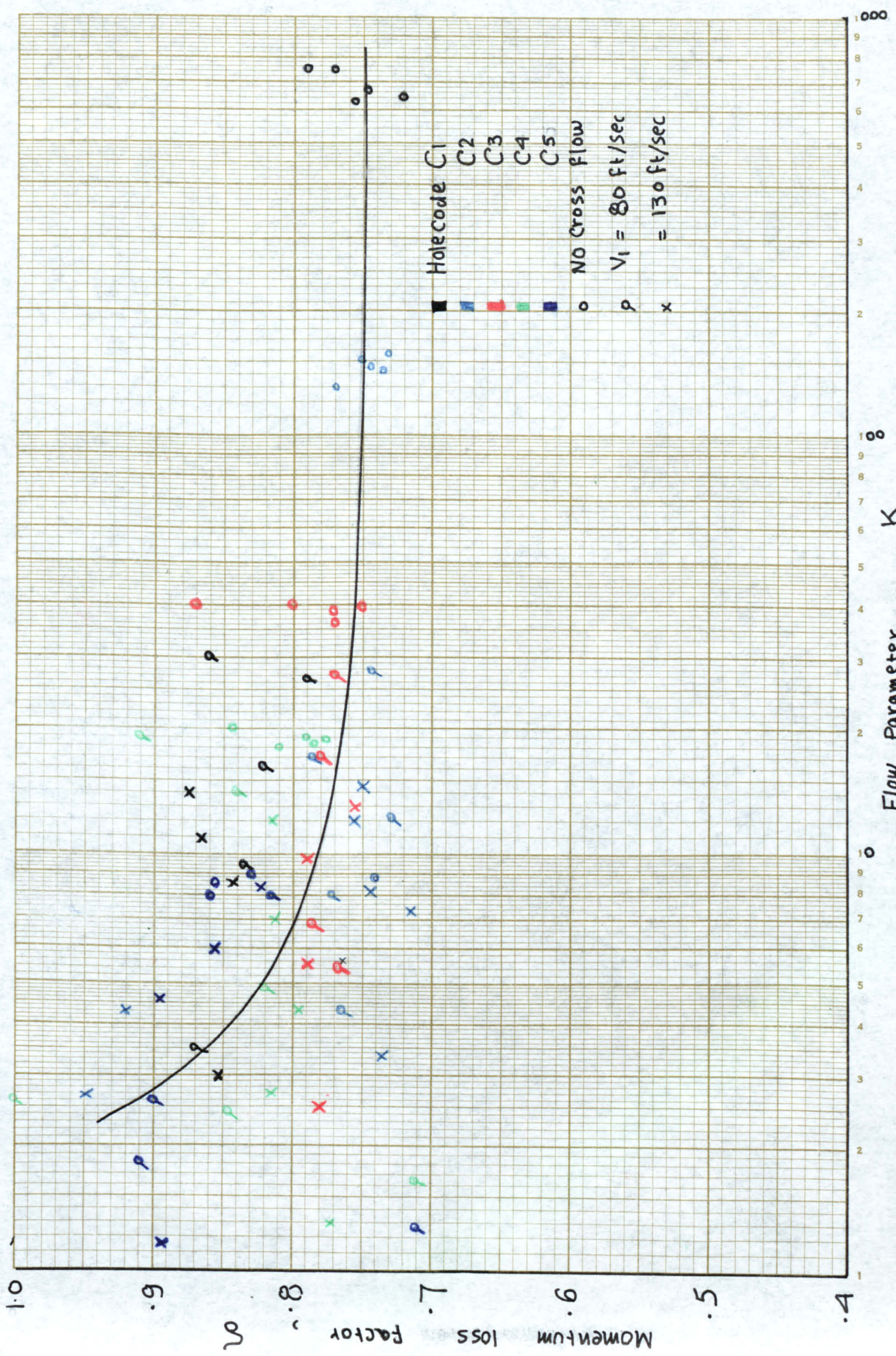
Variation of Flow Parameter with ratio of jet to approach velocities



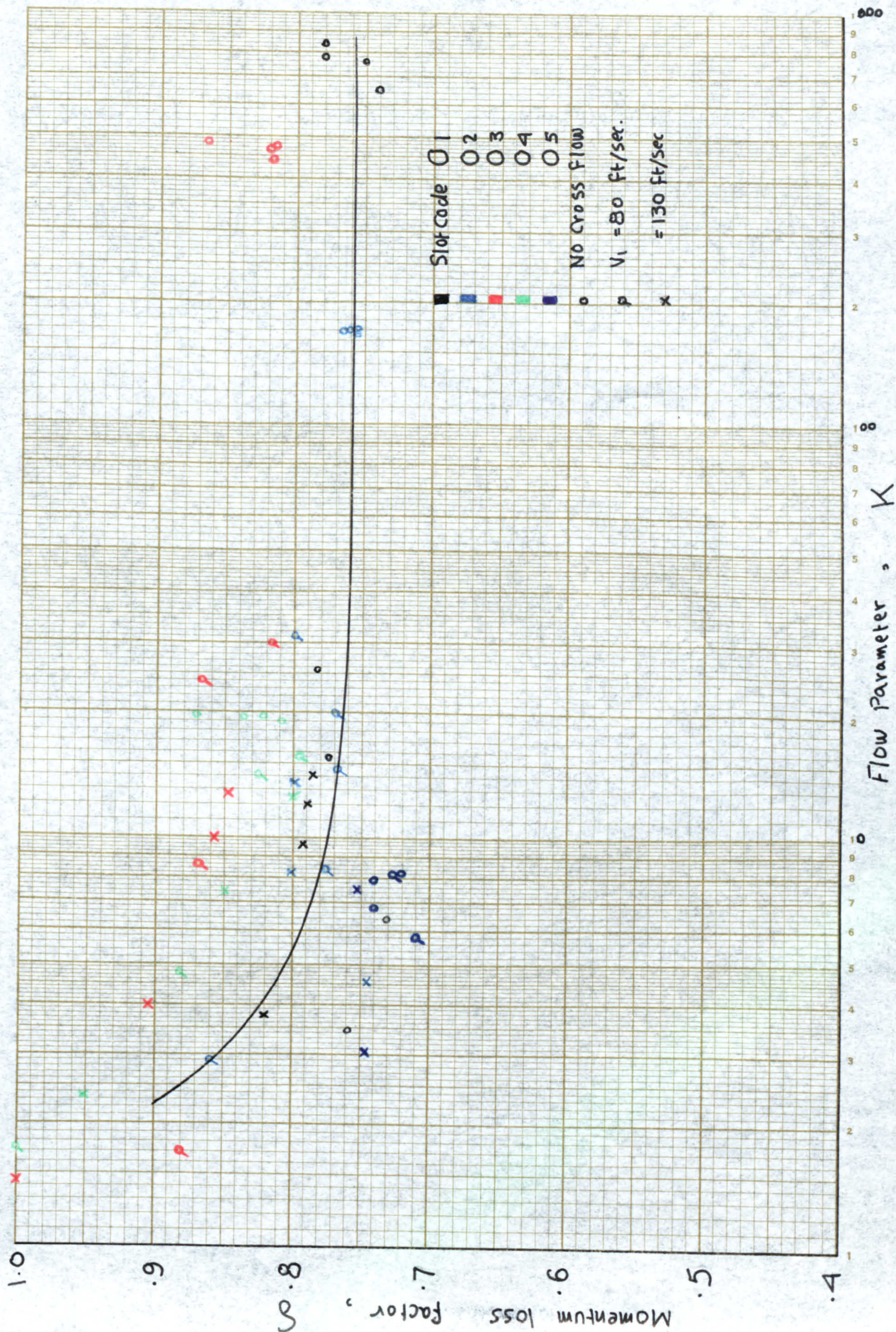
Theoretical Variation of Flow parameter with Flow factors

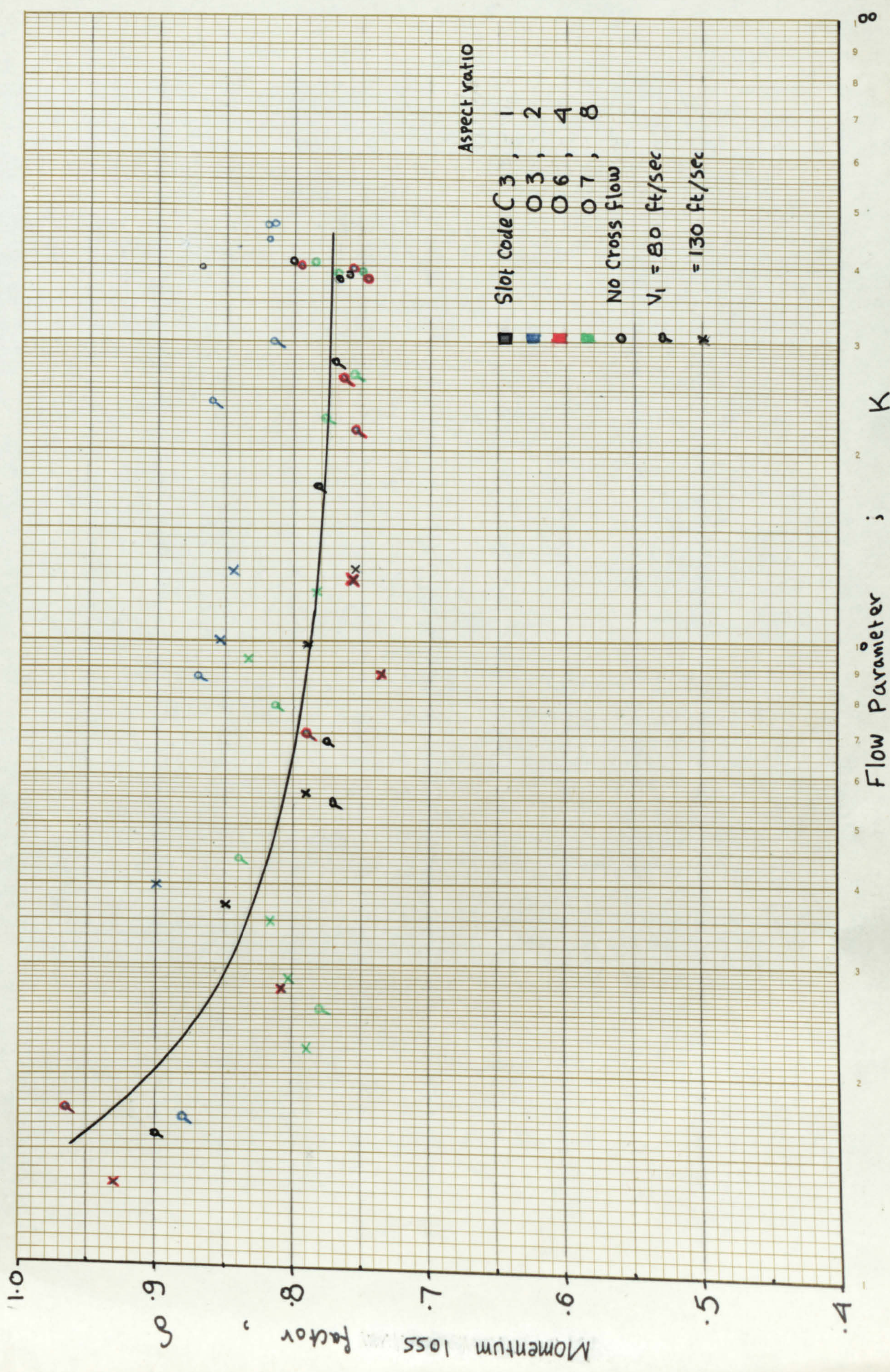


Theoretical Variation of approach velocity with area and pressure ratios. (No cross flow)

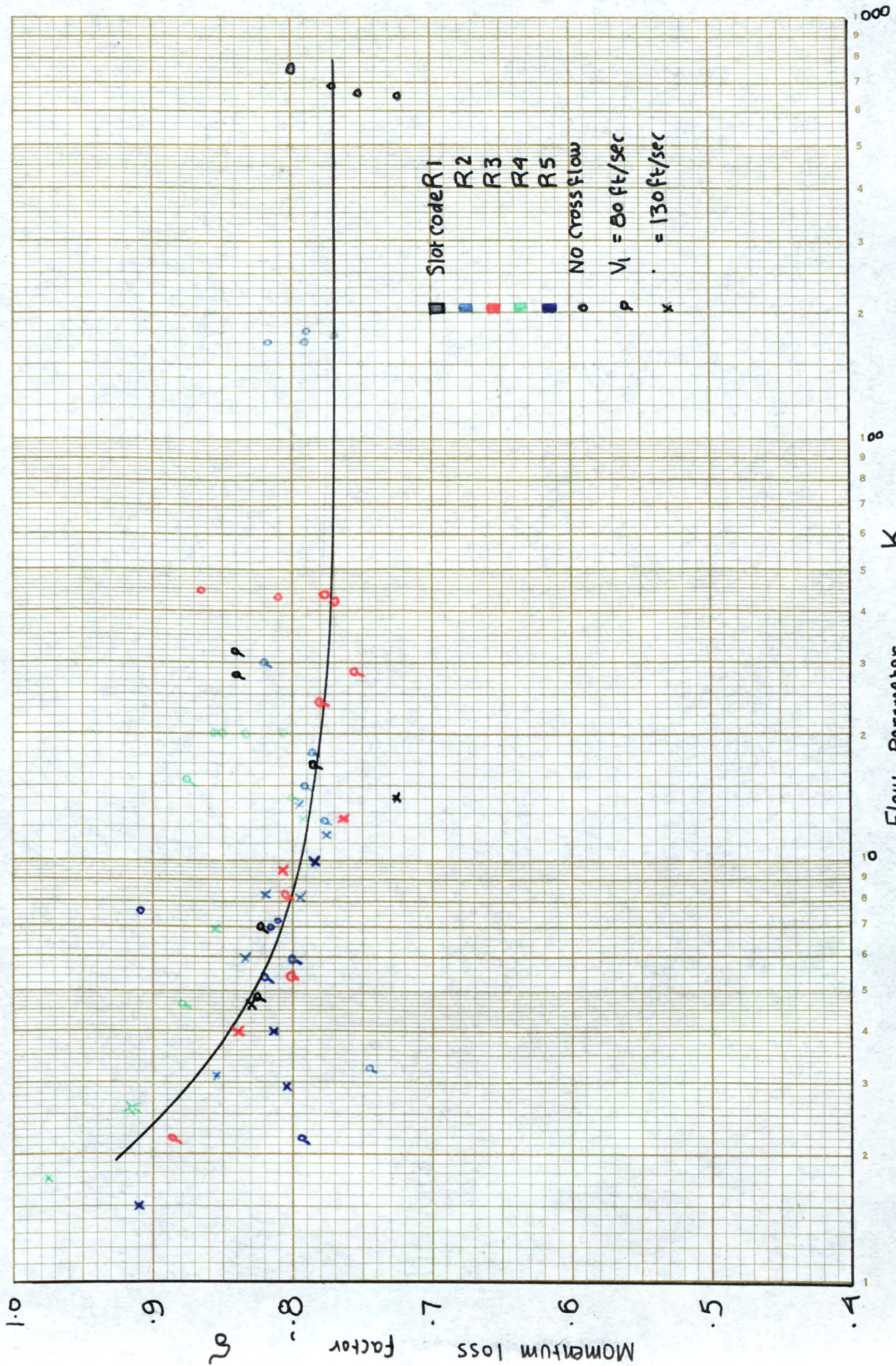


Momentum loss factor for circular holes — C₁ — C₅.

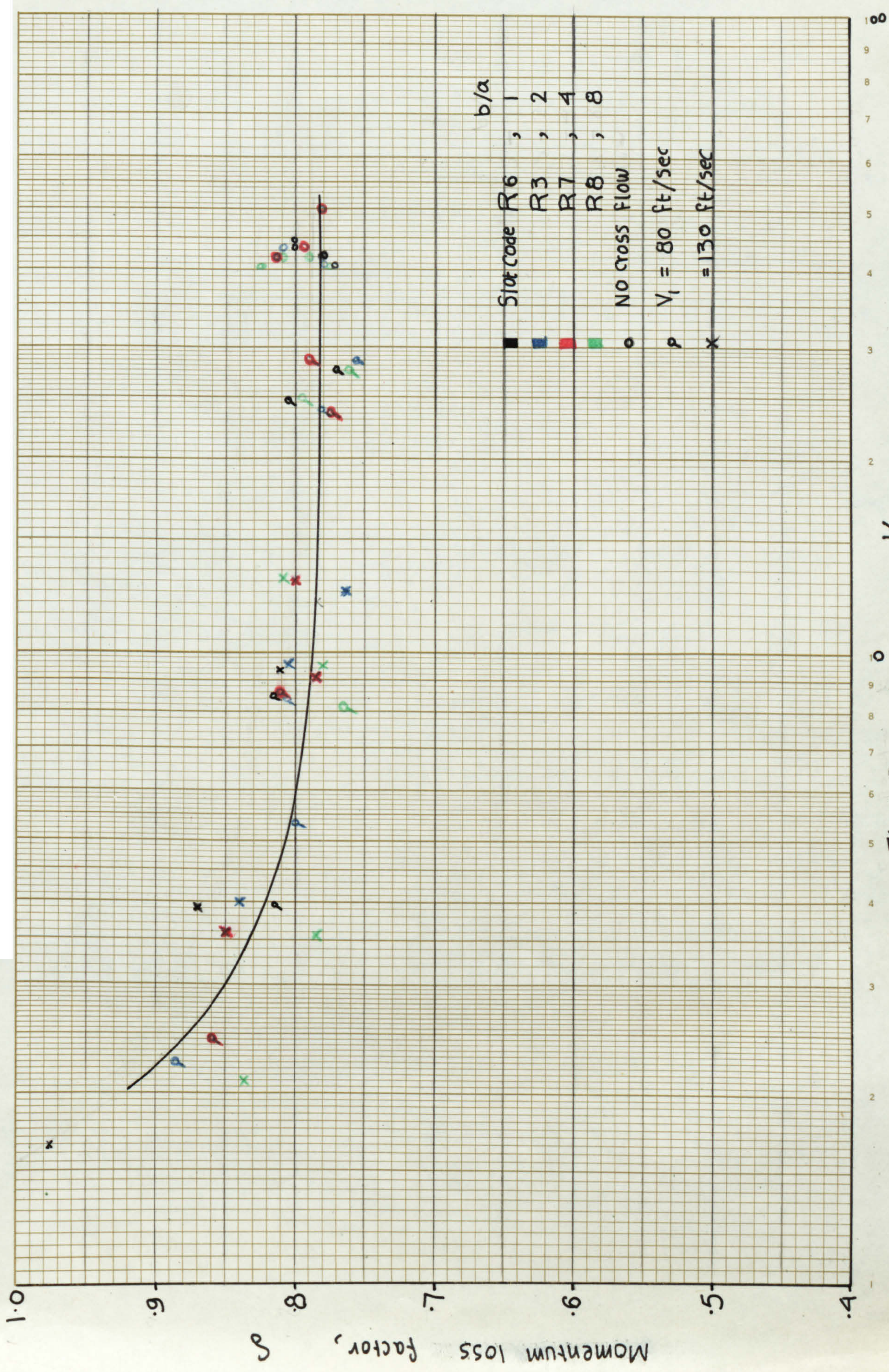




Momentum loss factor for oval slots - Area ratio $a^* = 0.252$.

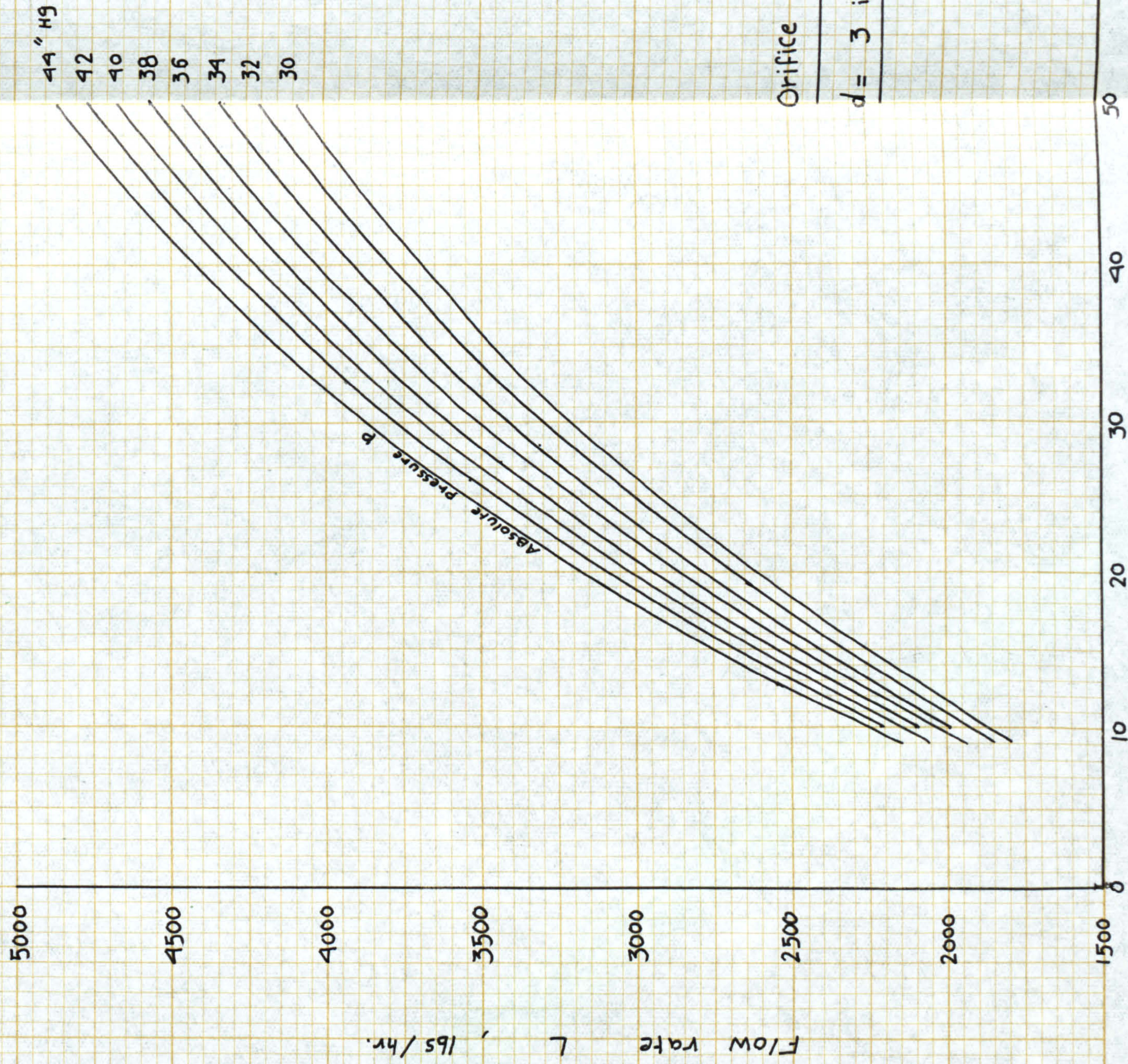


Momentum loss factor for Rectangular slots. Aspect ratio = 2.0



Momentum loss factor for Rectangular slots - Area ratio = 0.252

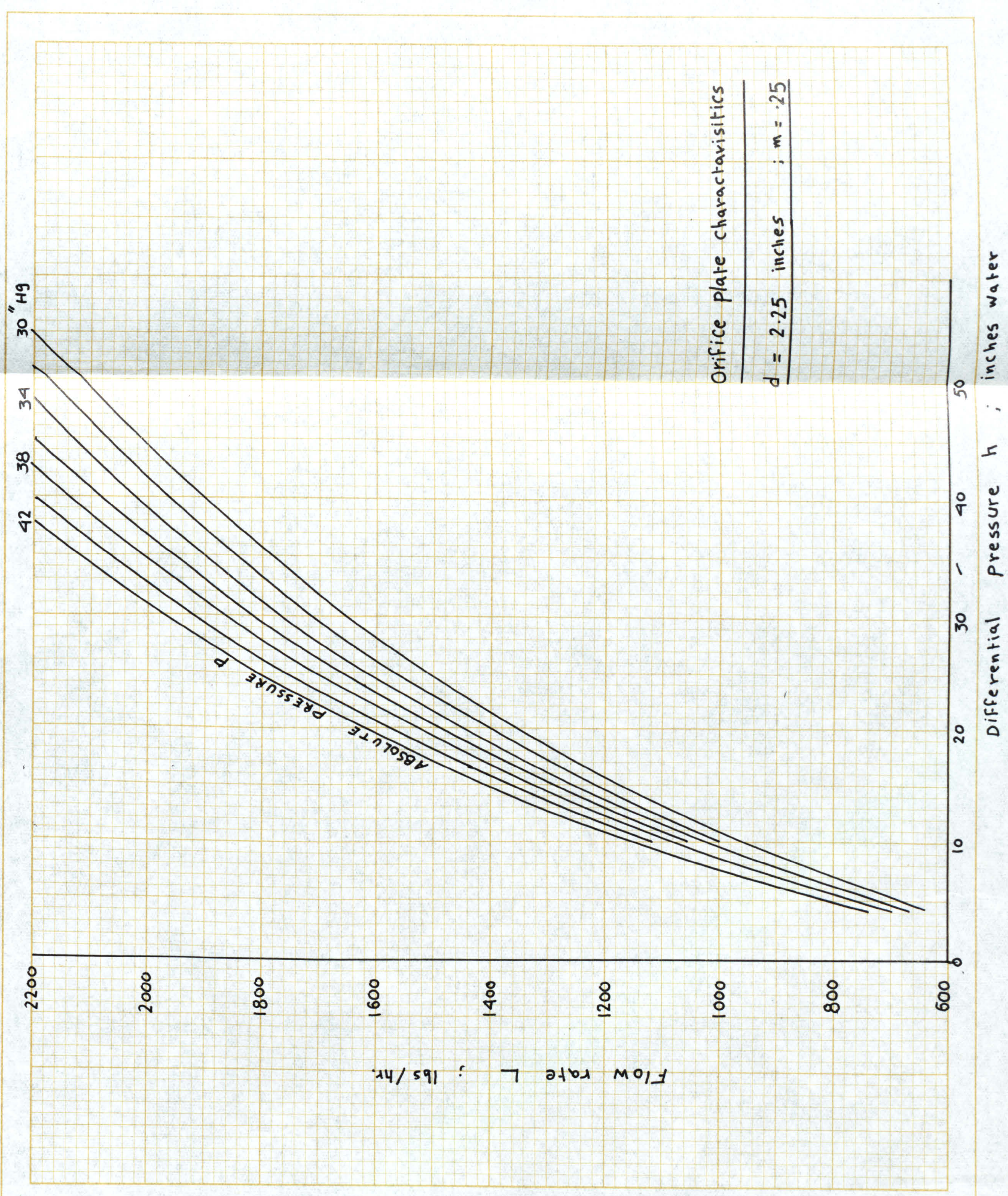
FIG-A3-1

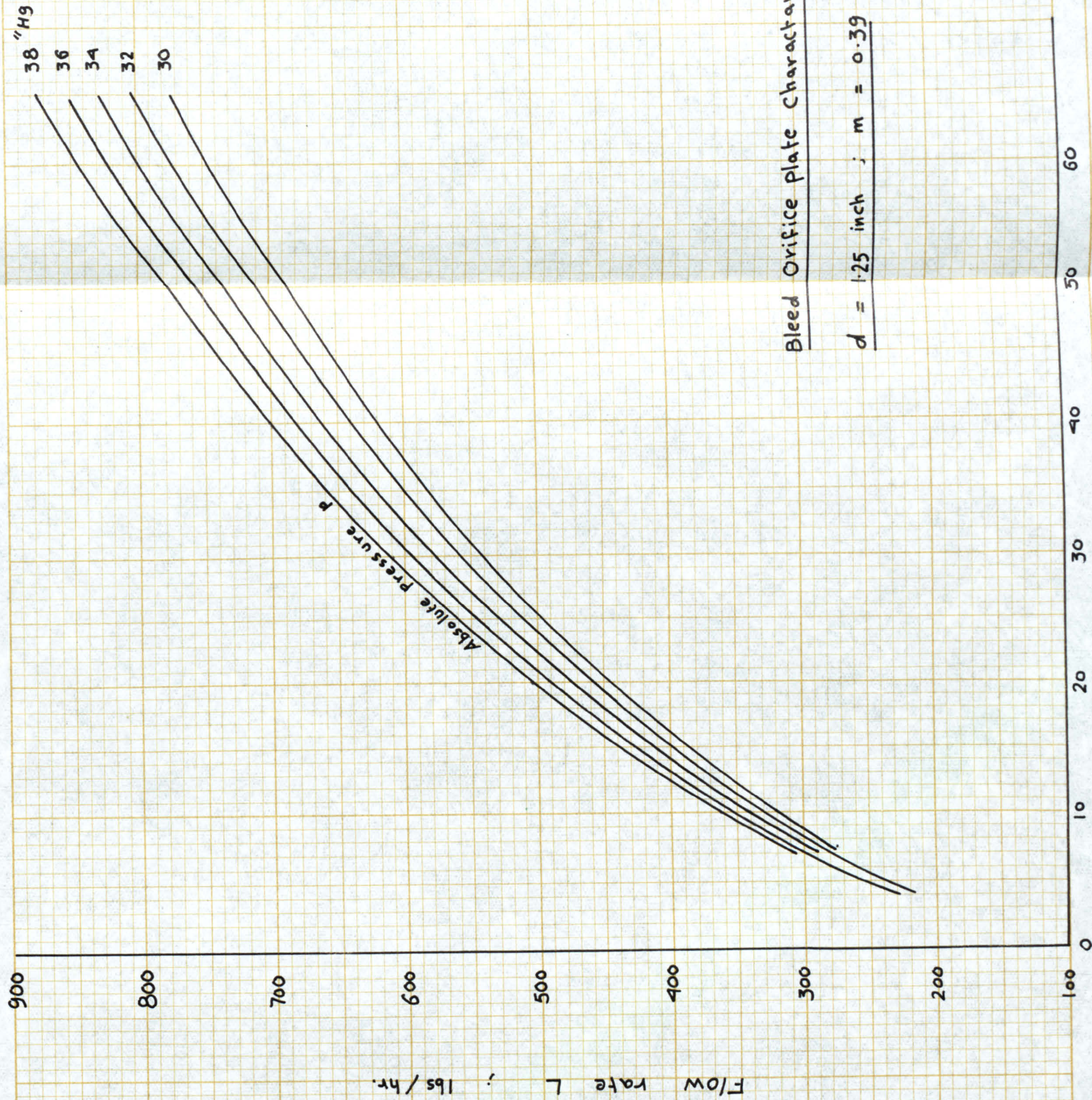


Orifice plate characteristics

$d = 3$ inches ; $m = .445$

FIG-A3-2

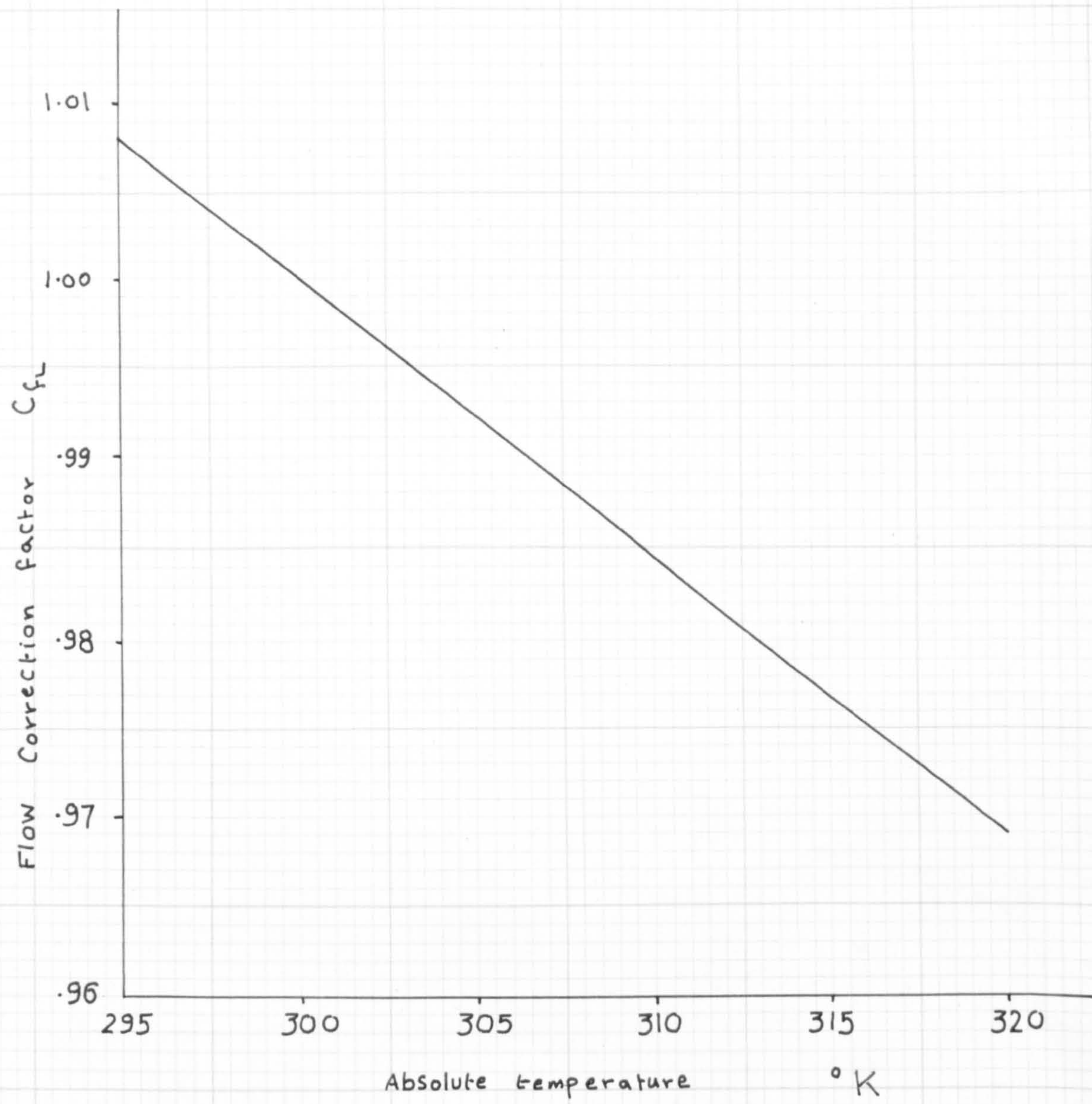




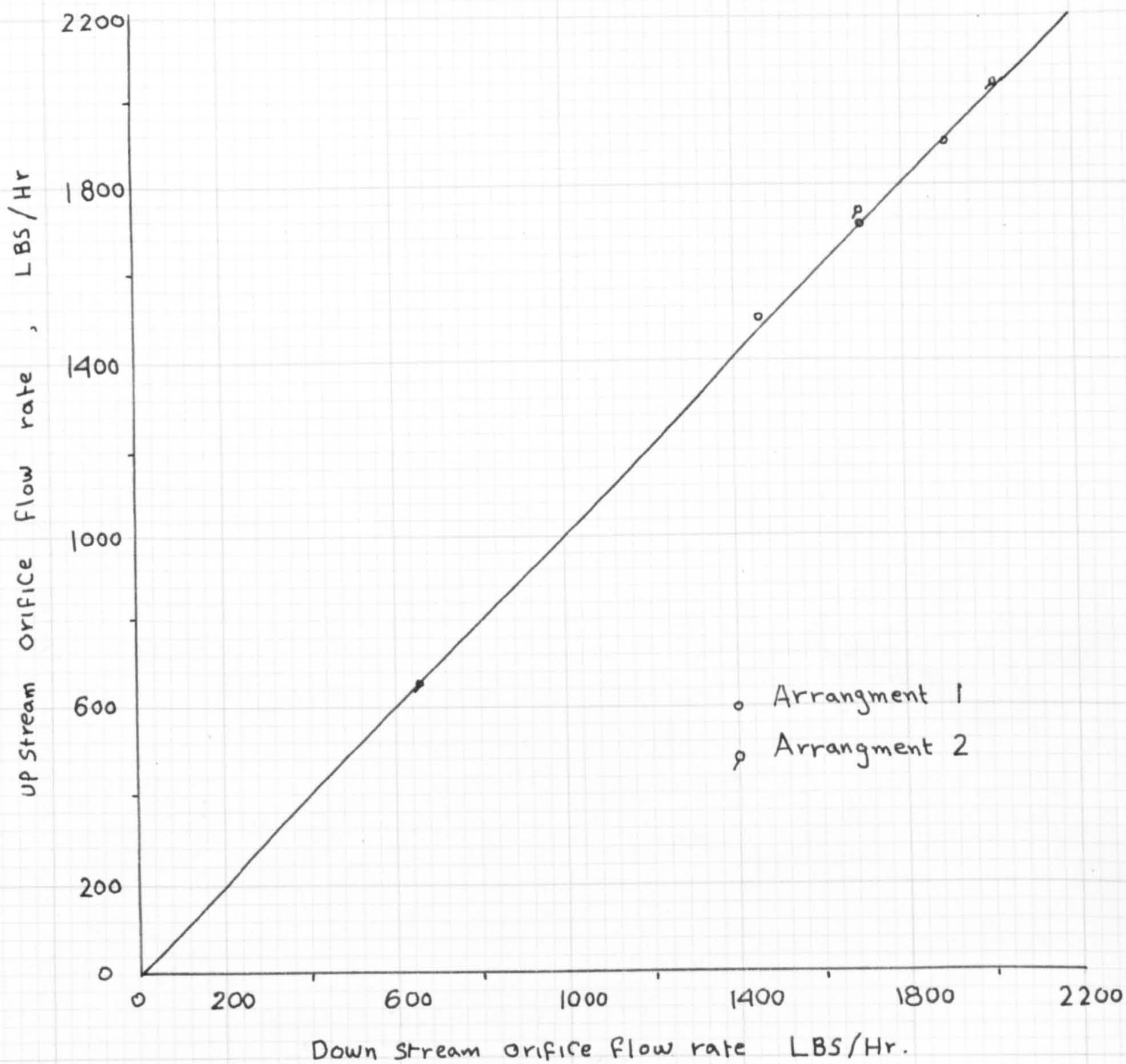
Bleed Orifice plate Characteristics

$d = 1.25 \text{ inch} ; m = 0.39$

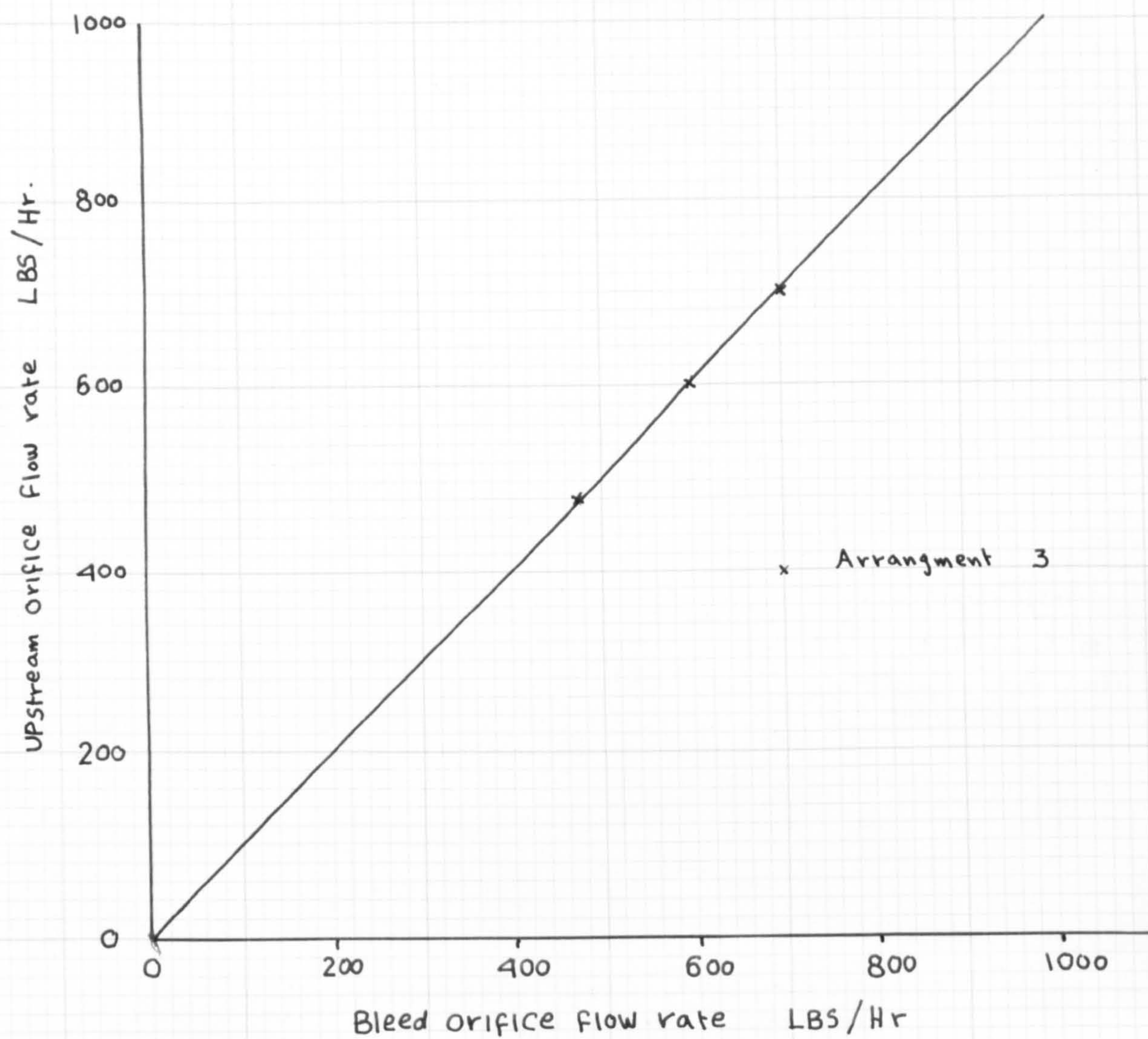
Differential pressure h ; inches water



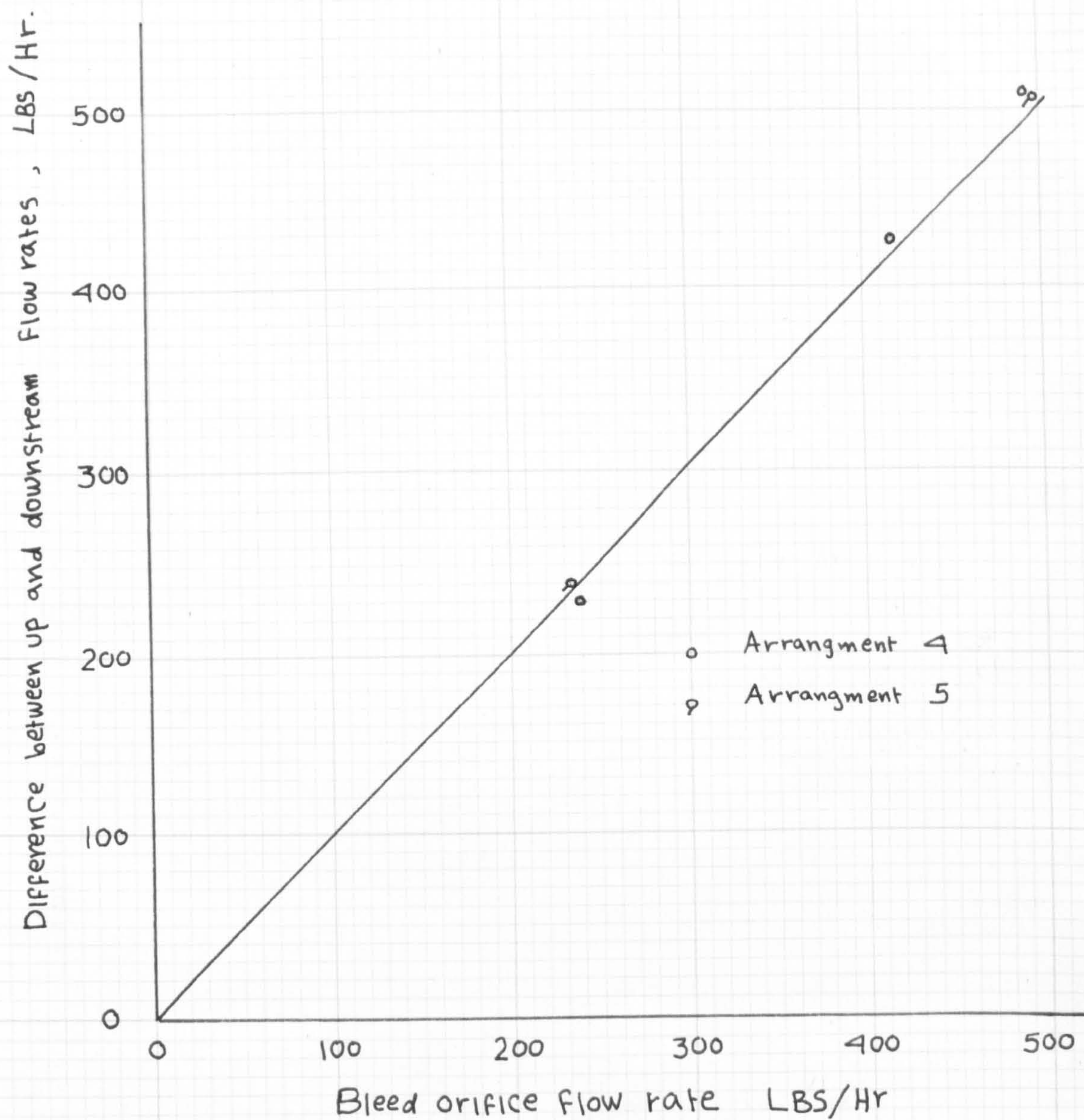
Temperature Correction for flow rate



Orifice Plate Calibration

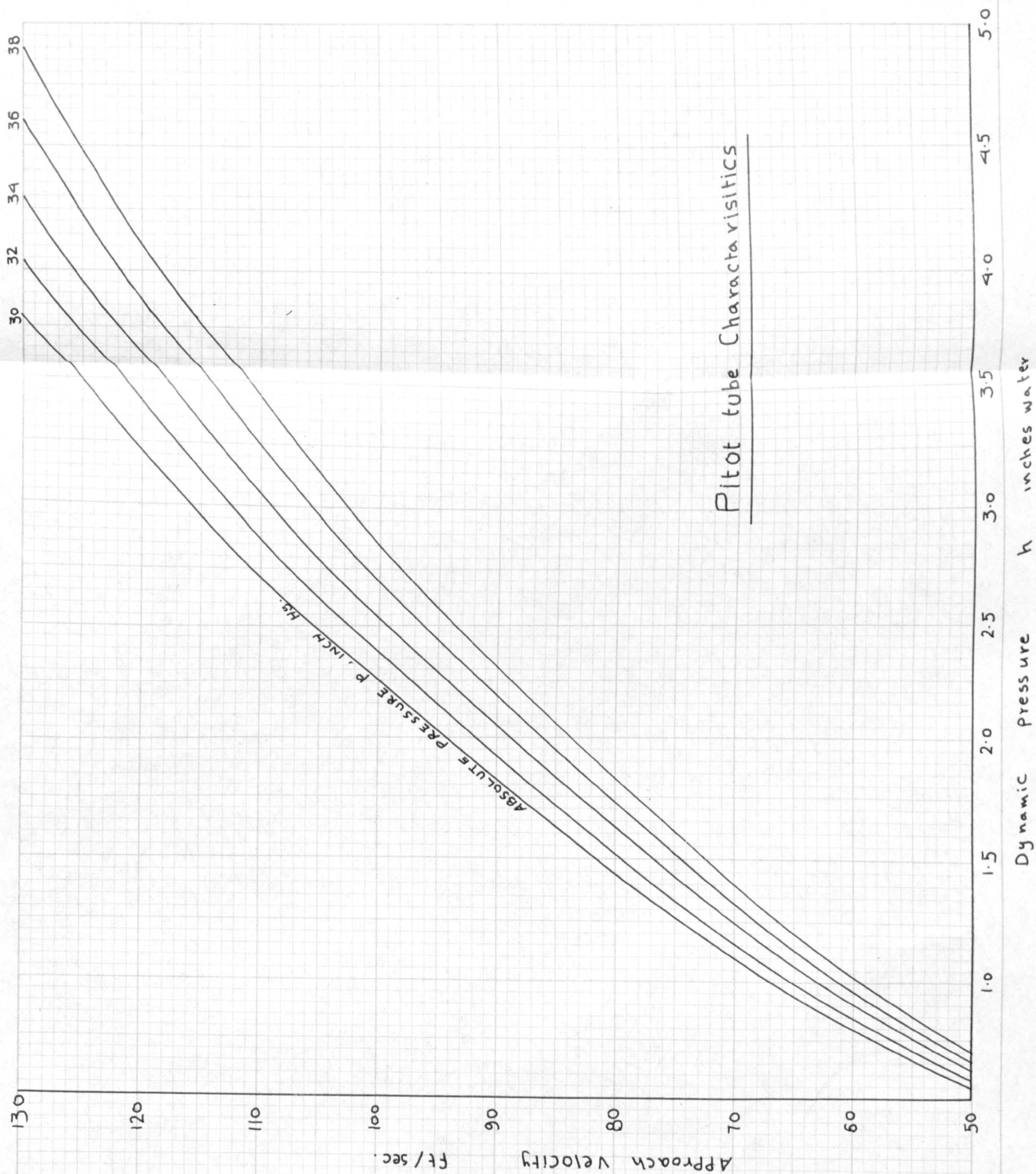


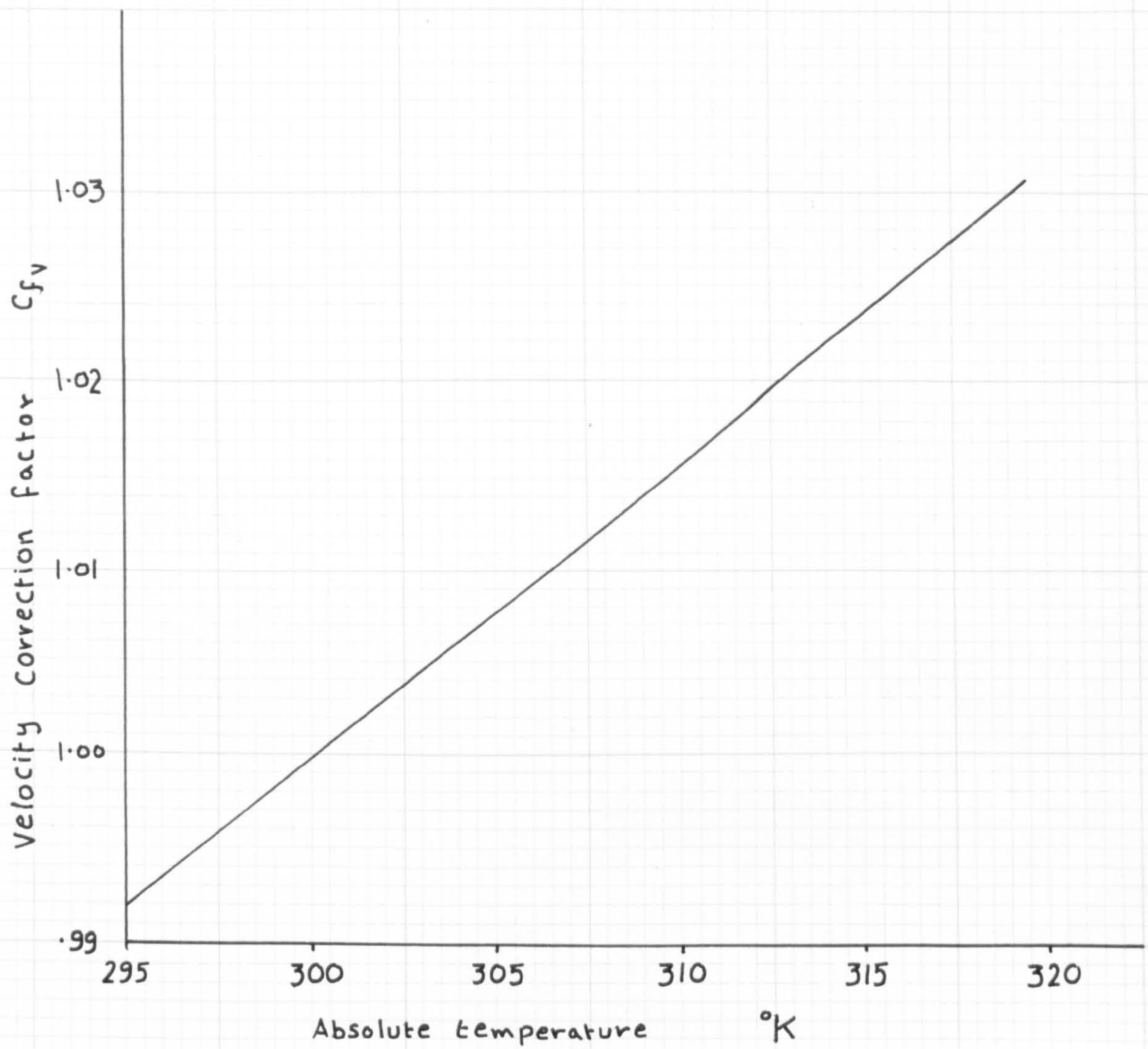
Orifice plate calibration



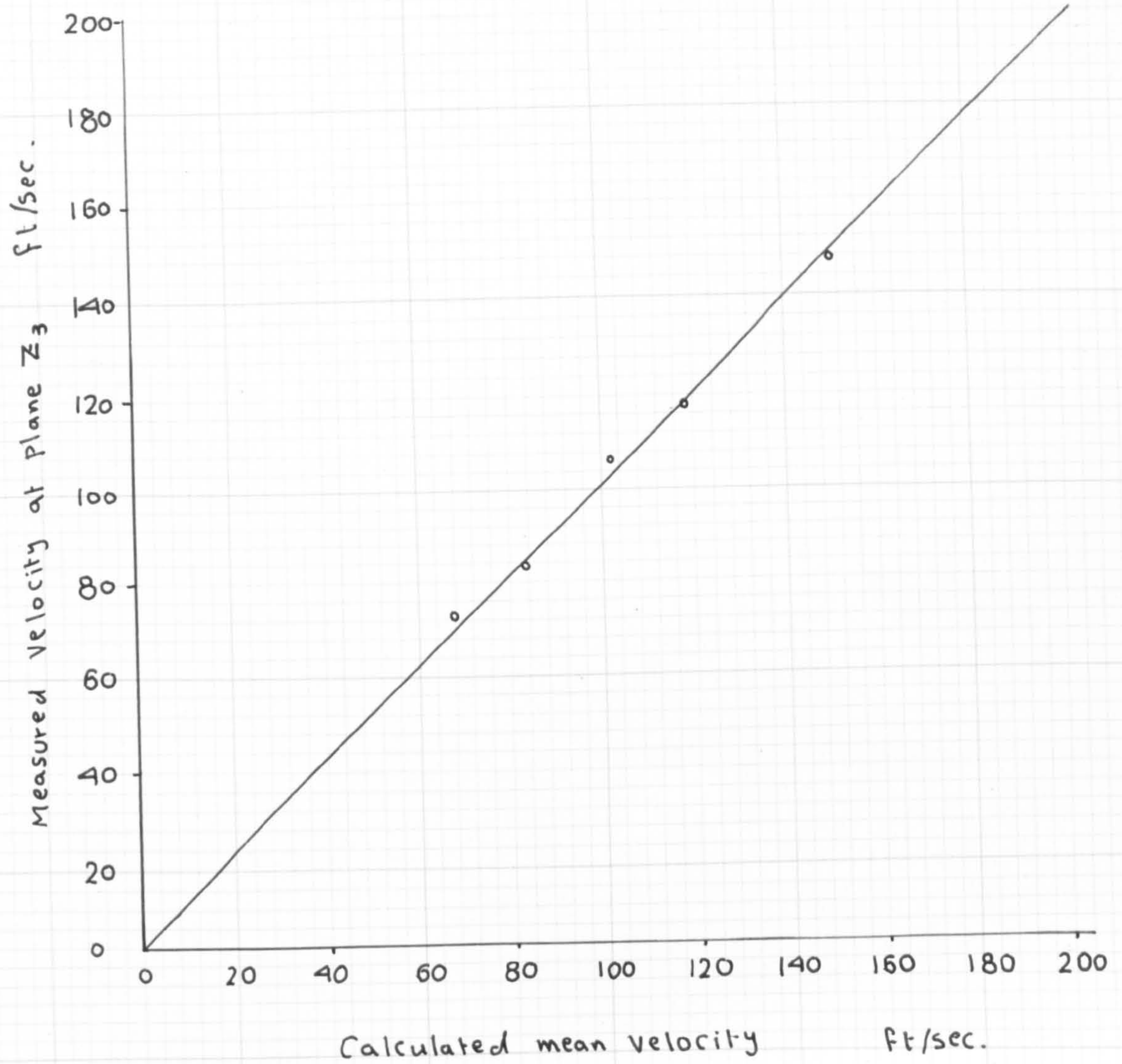
Orifice plate calibration

FIG-A3-8

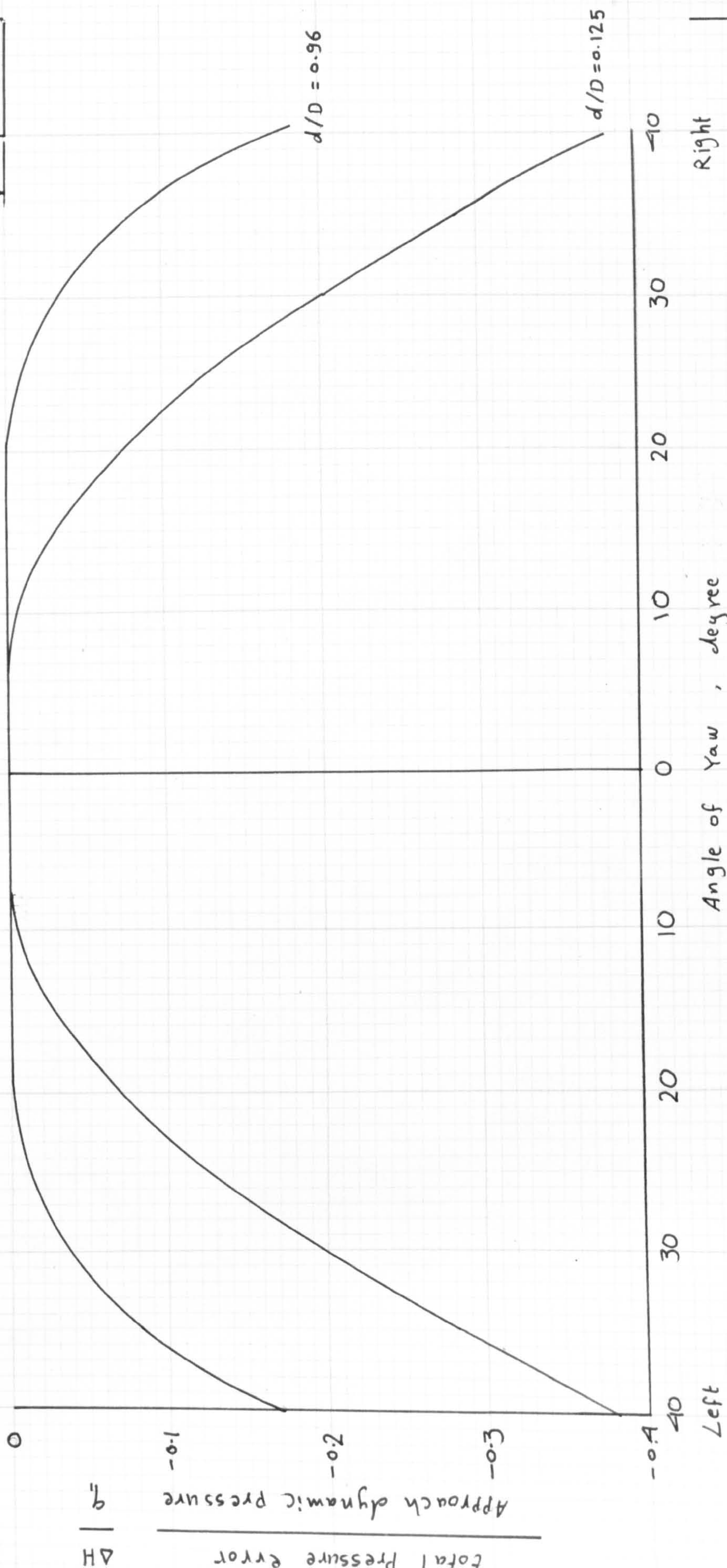




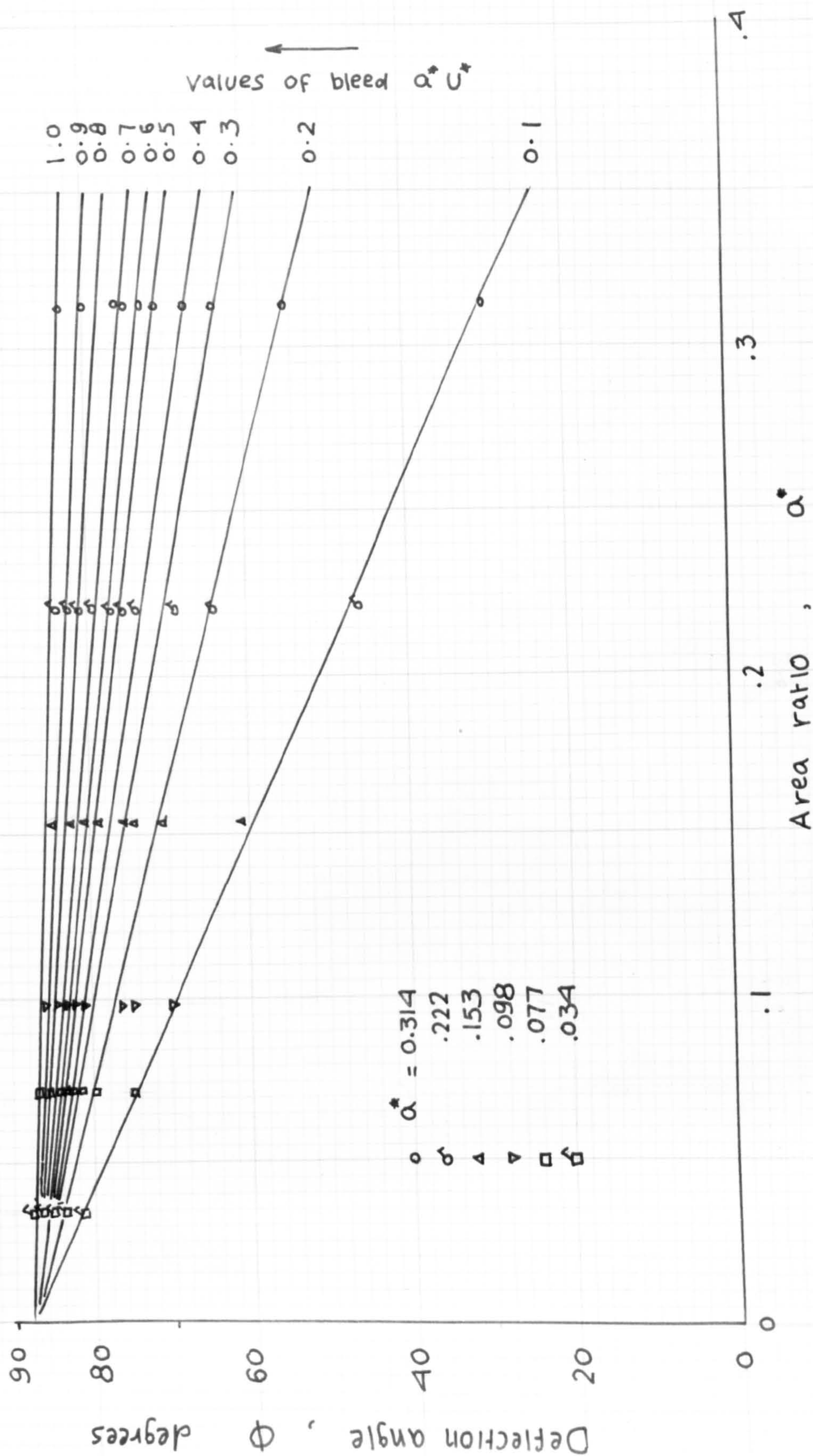
Temperature Correction for velocity



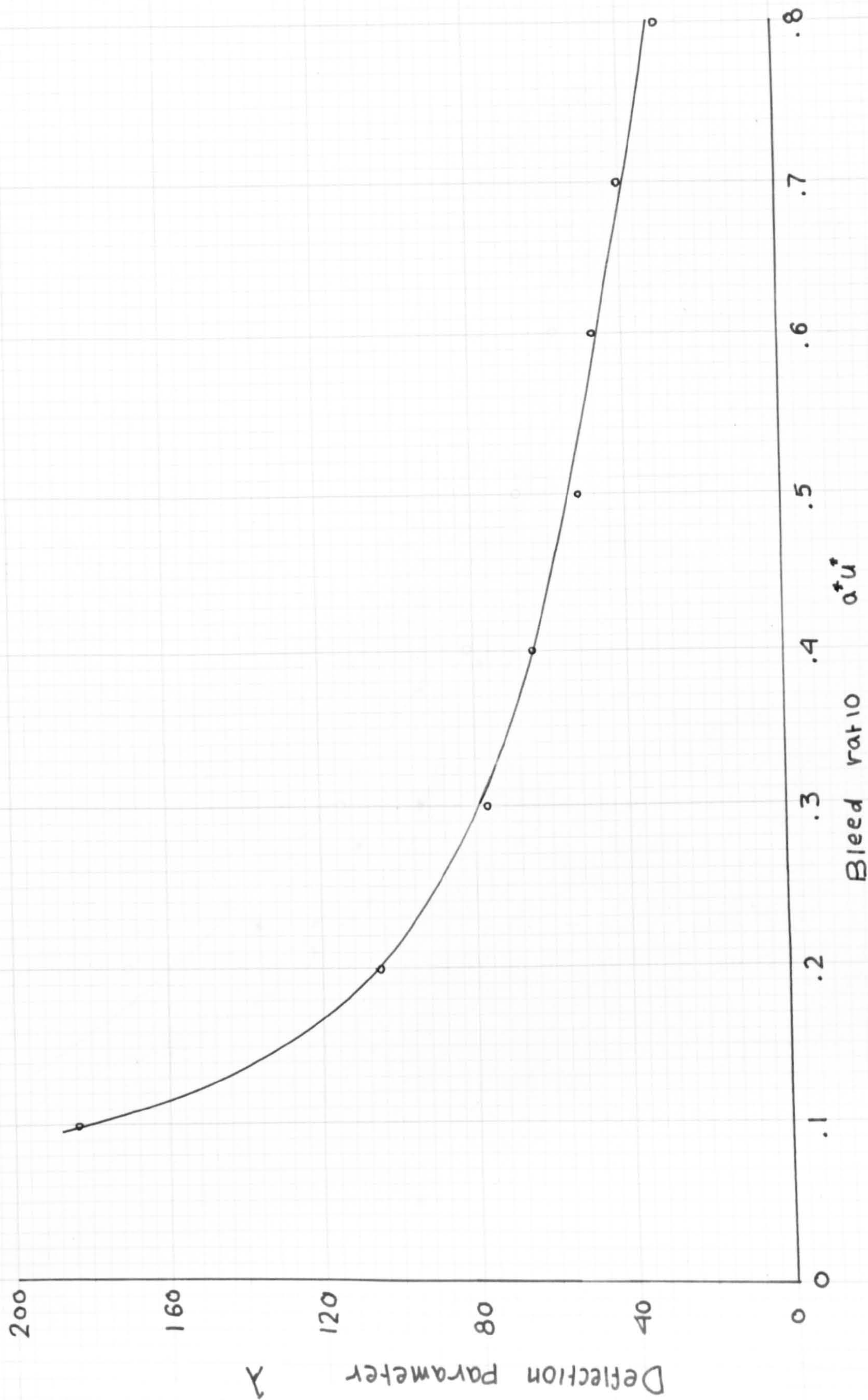
Pitot tube Calibration



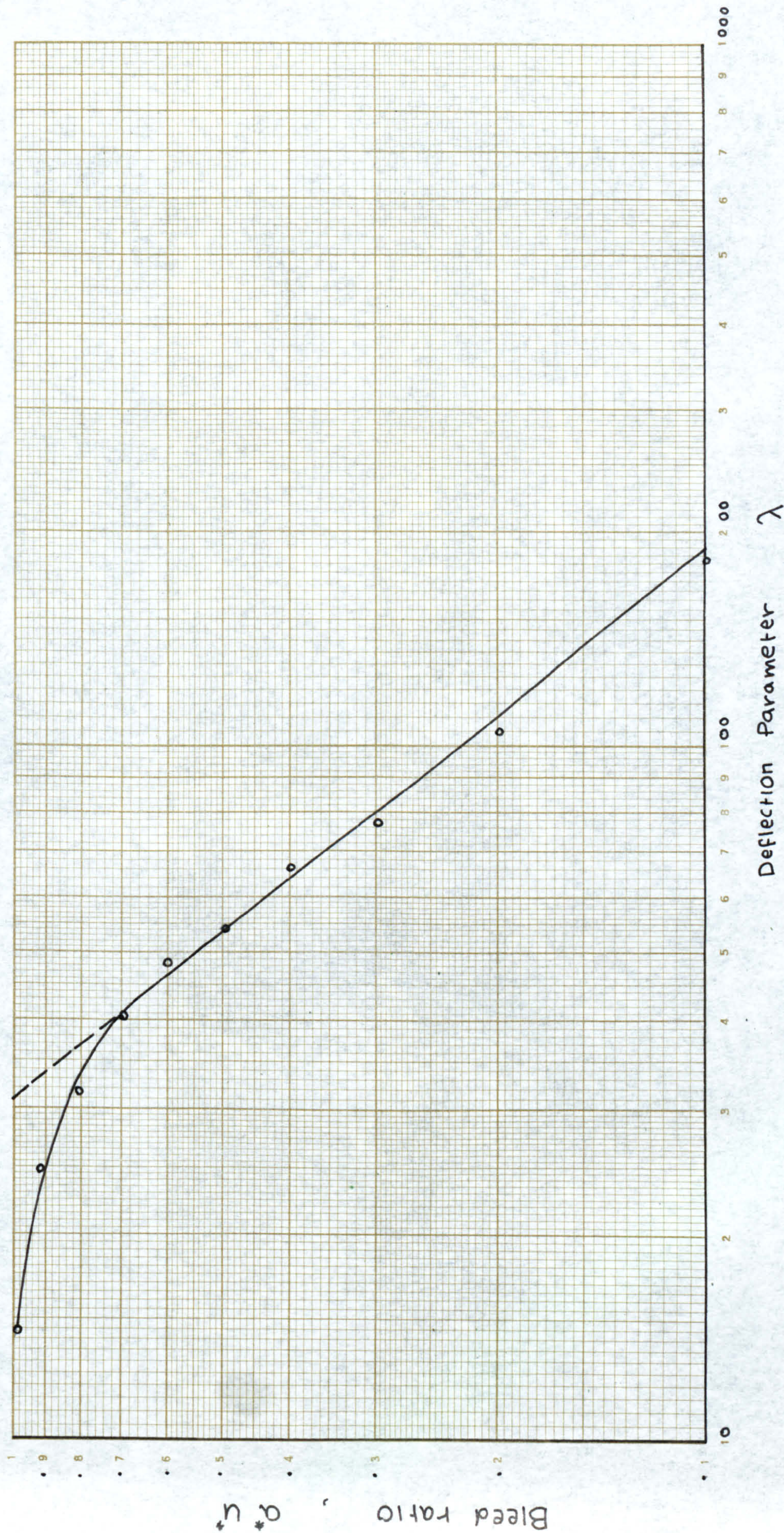
Variation of total pressure error with Yaw angle for cylindrical nose [11]



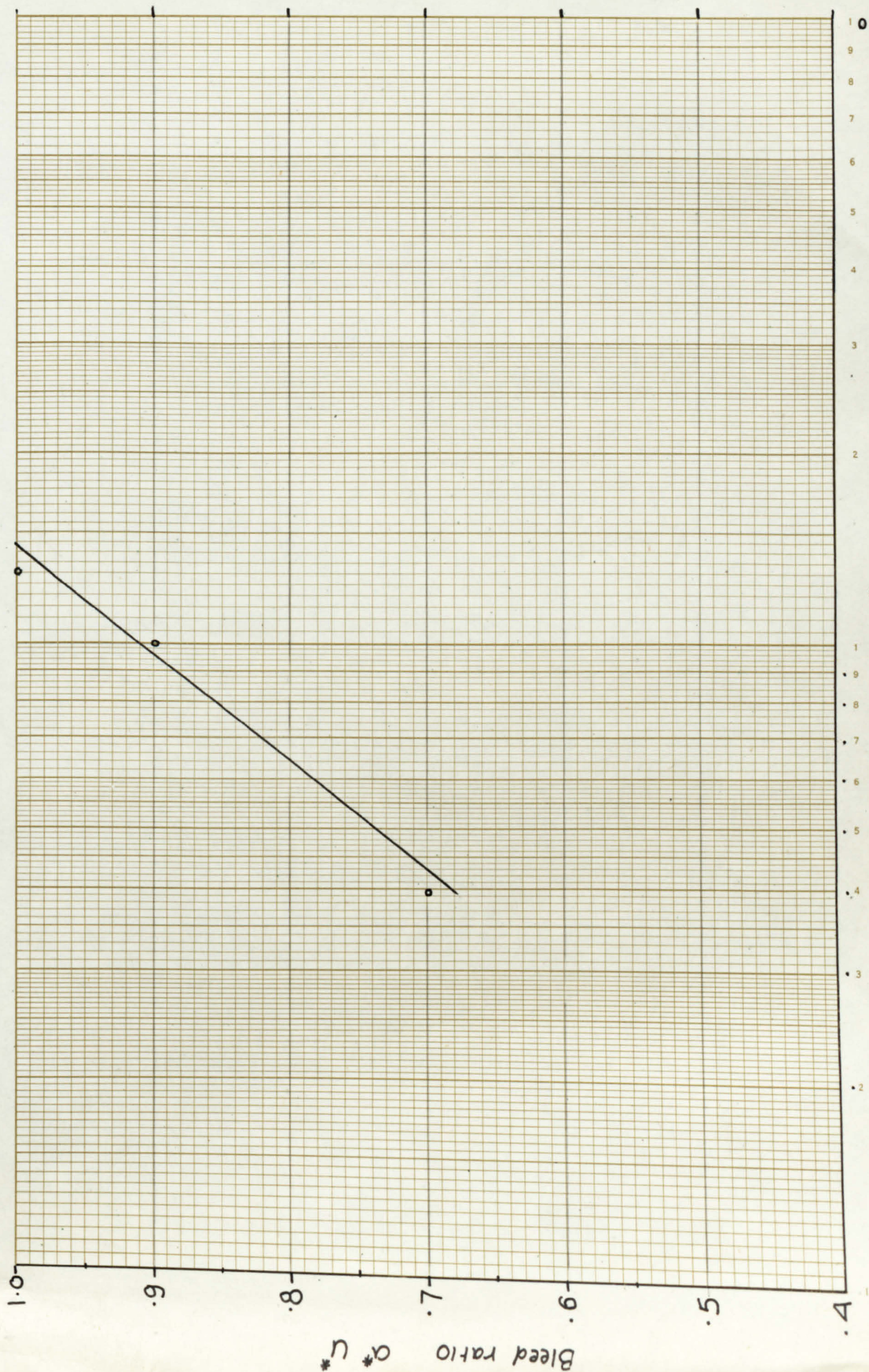
Variation of deflection angle with Area and Bleed ratios (7)



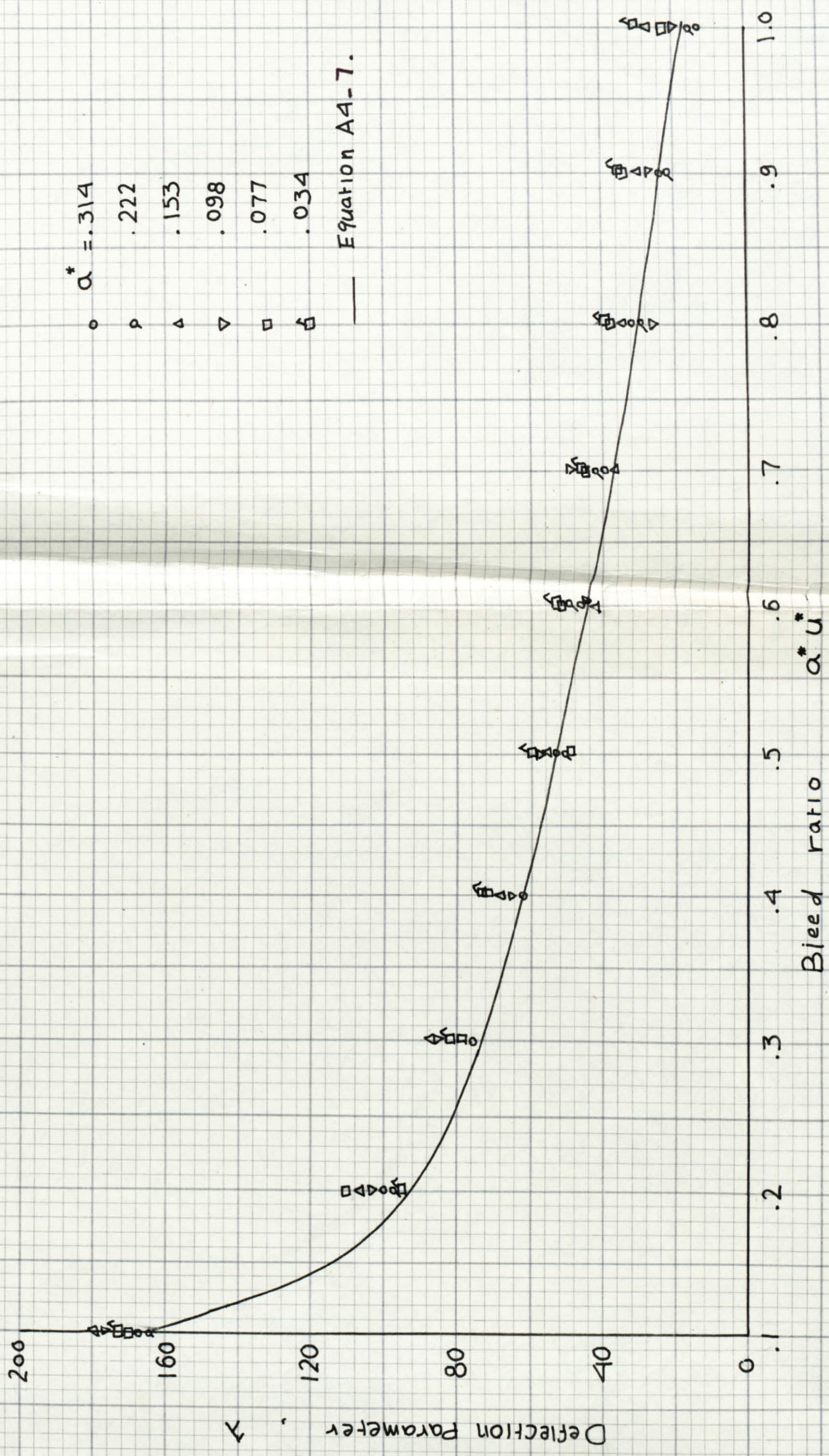
Variation of Deflection parameter with Bleed ratio (7)



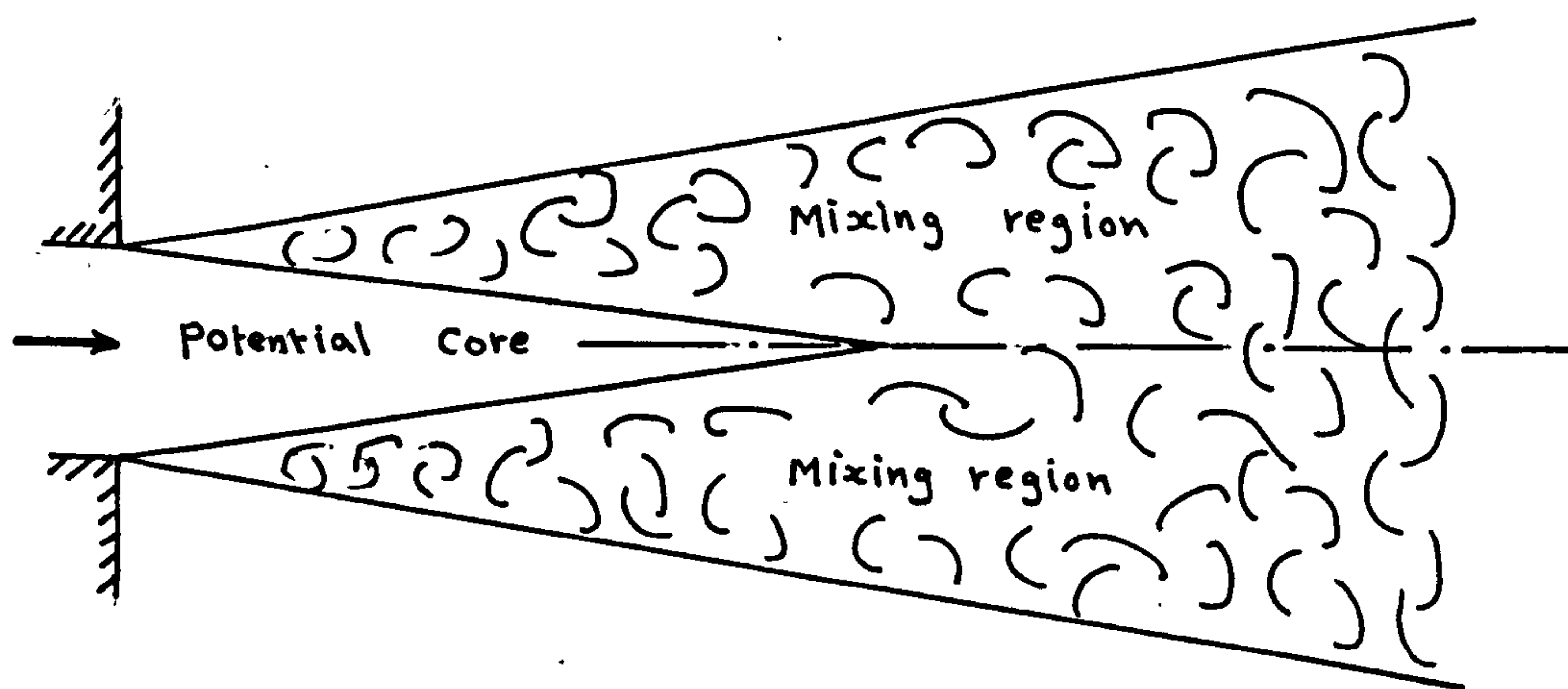
Variation of Deflection parameter with Bleed ratio $\cdot (7)$



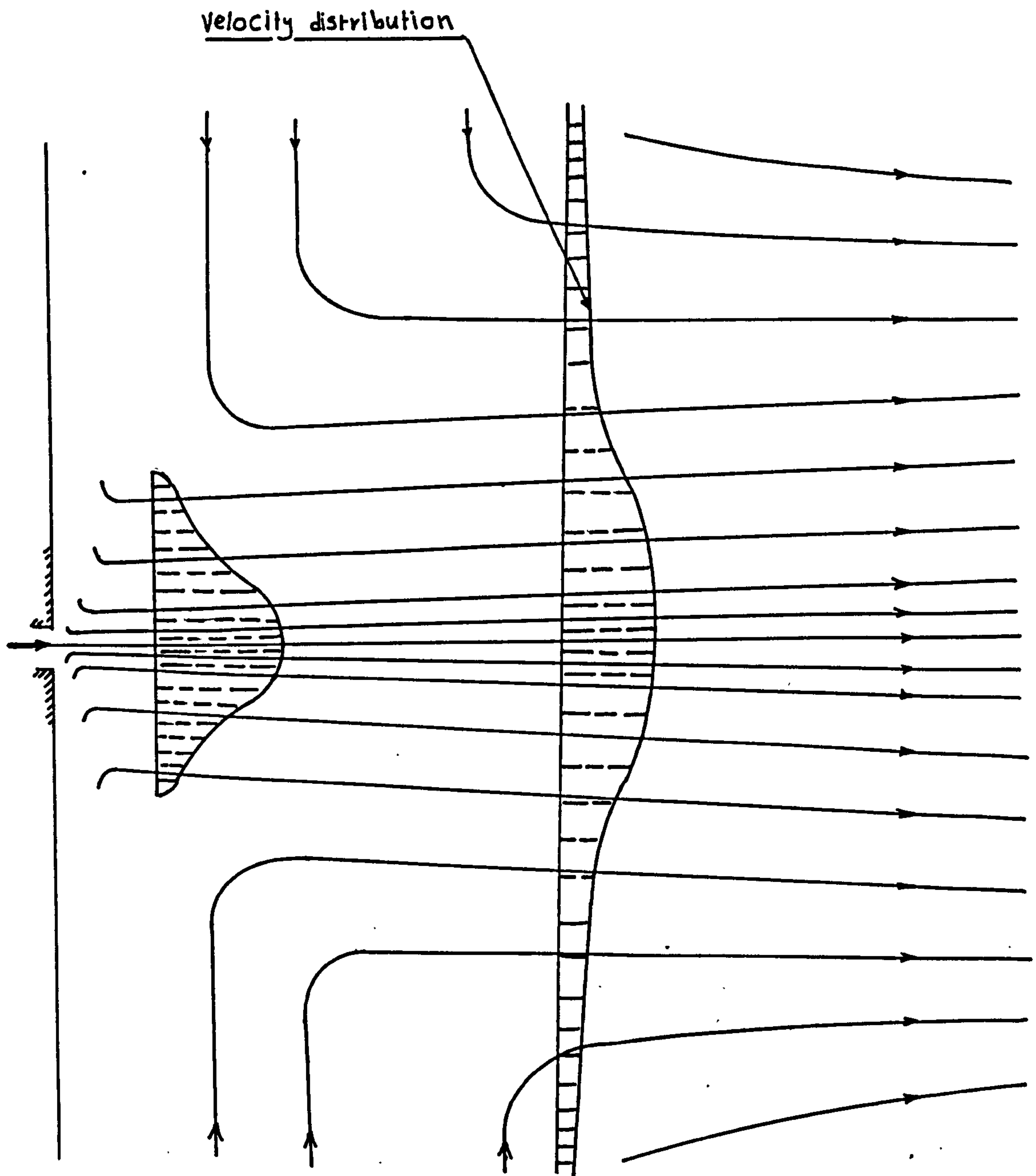
Variation of Log. with Bleed ratio - (. 7 a U 1.0) . [7]



Variation of Deflection parameter with Bleed ratio for circular holes (7)



Typical jet regions



Jet structure - increase in concentration
with decrease in velocity downstream.

PHOTOGRAPHIC PLATES



Plate 1

GENERAL RIG LAYOUT AT ALLIS CHALMERS

TEST HOUSE

Test Section is partially behind the manometers,
flow direction from left to right.

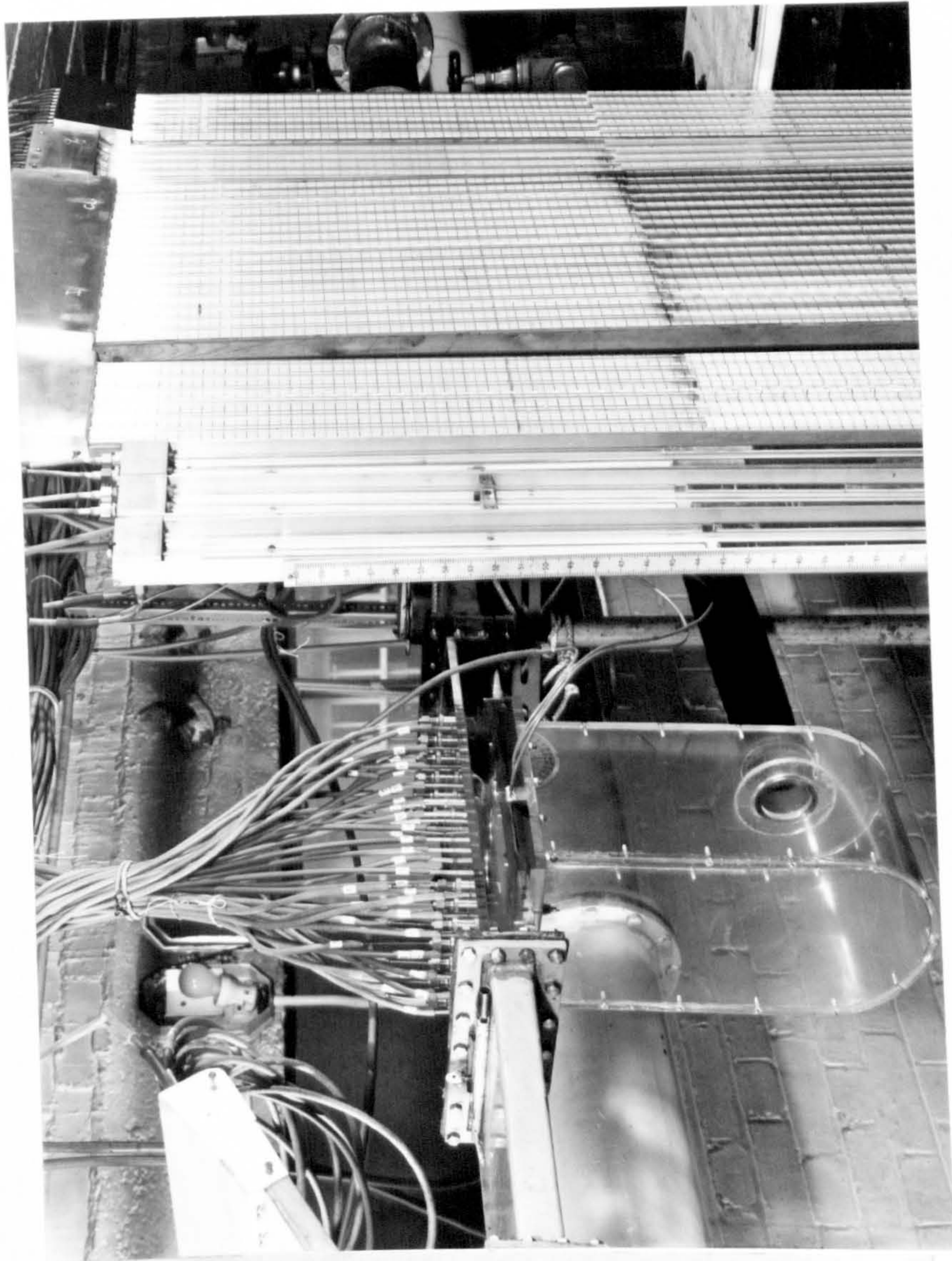


Plate 2

COMPLETE TEST SECTION MOUNTED ON THE RIG

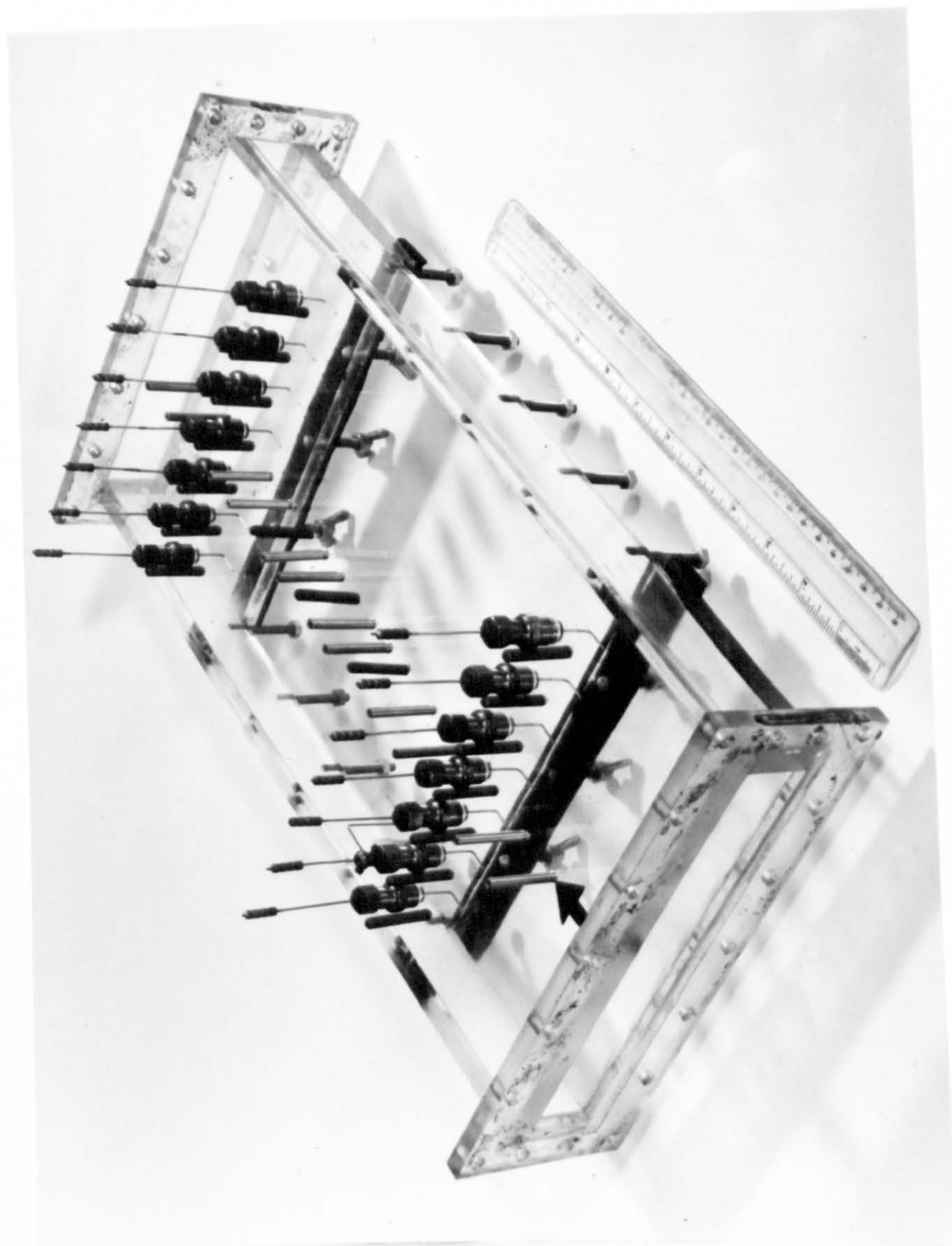


Plate 3

MODIFIED TEST SECTION

Static pressure measurement at seventeen stations along duct centre line.

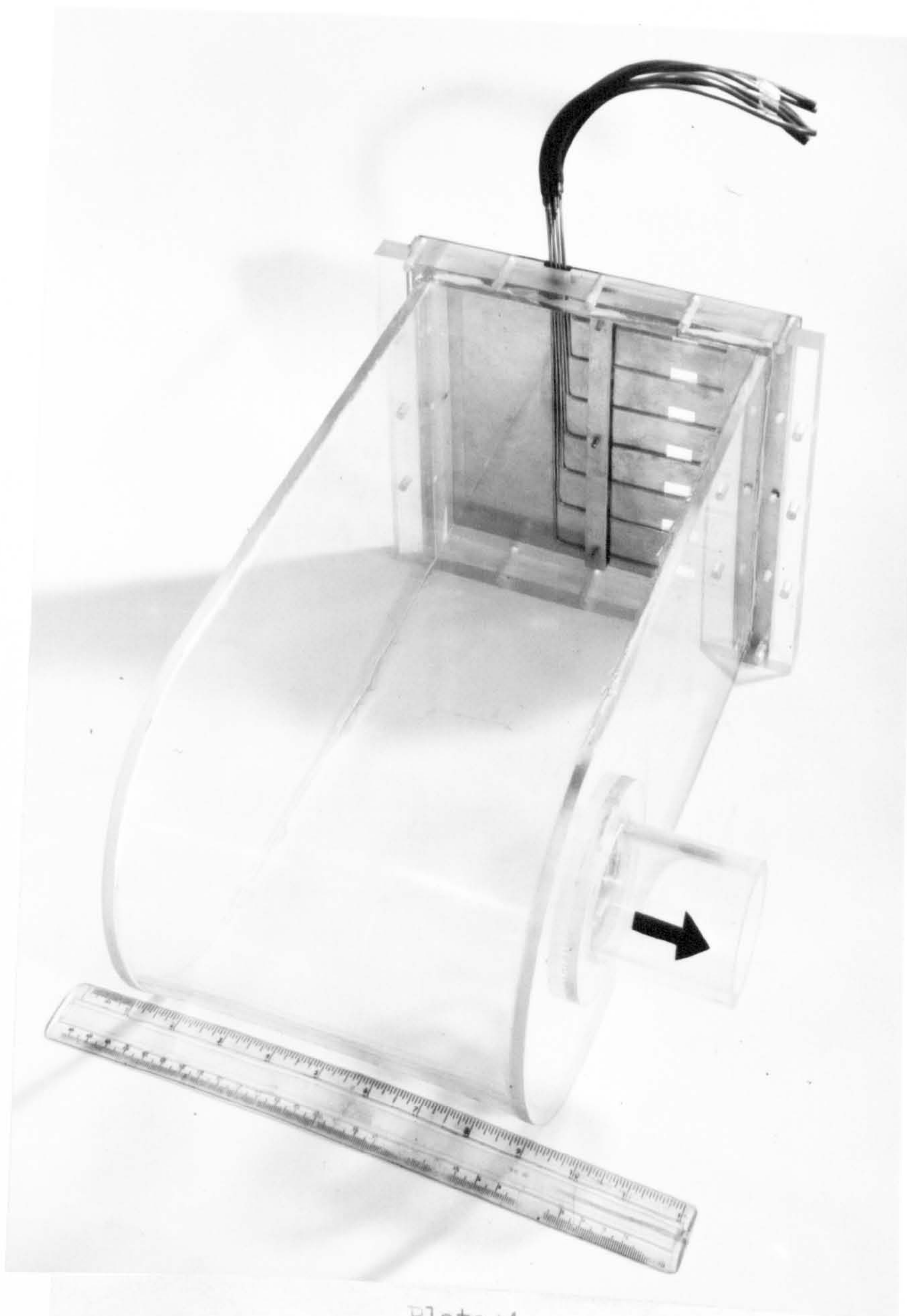


Plate 4

PLENUM CHAMBER WITH TEST PLATE IN POSITION

Notice the position of jet static probes.

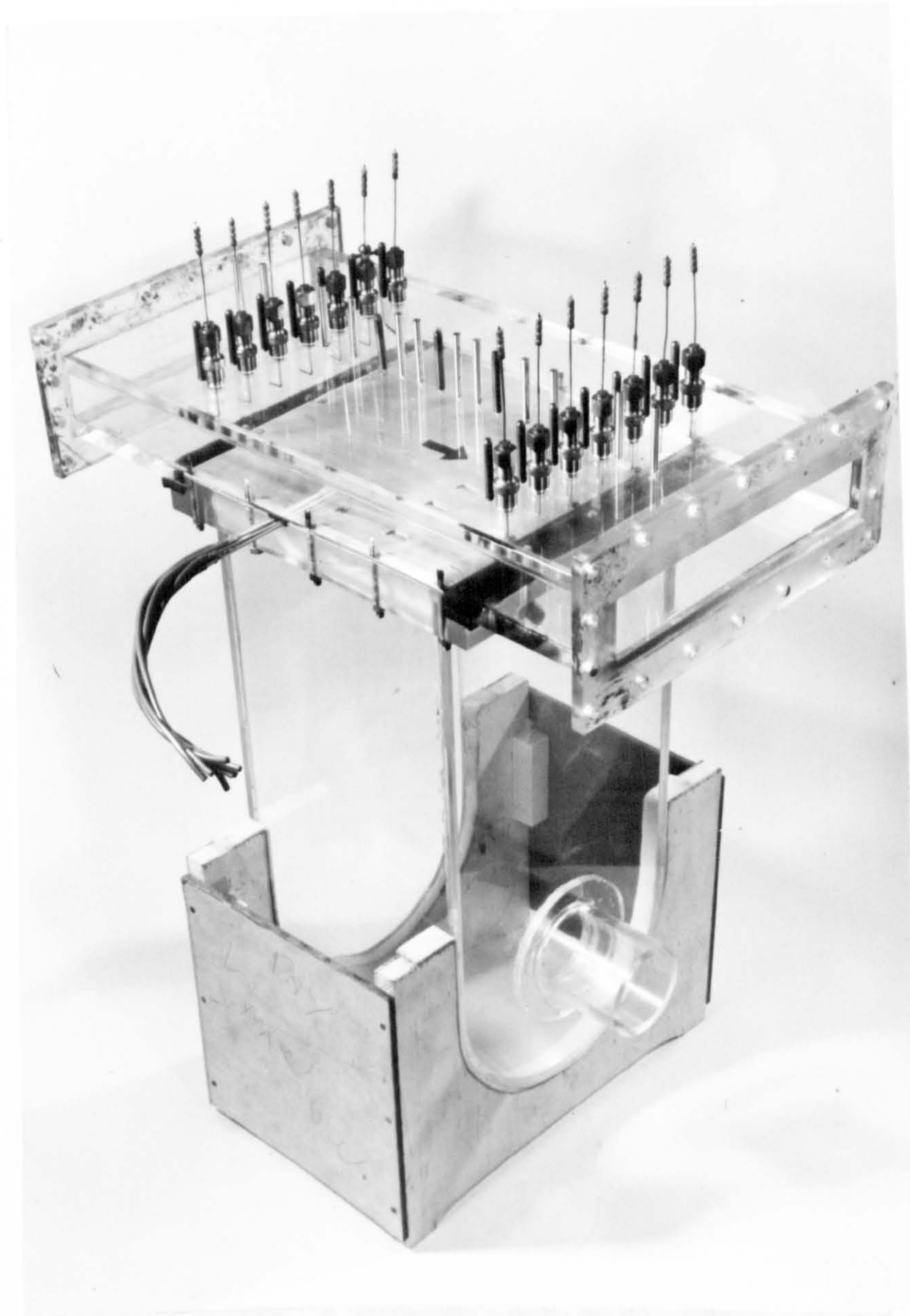


Plate 5

TEST SECTION COMPLETE

Plenum chamber assembled with test section,
test plate in position.

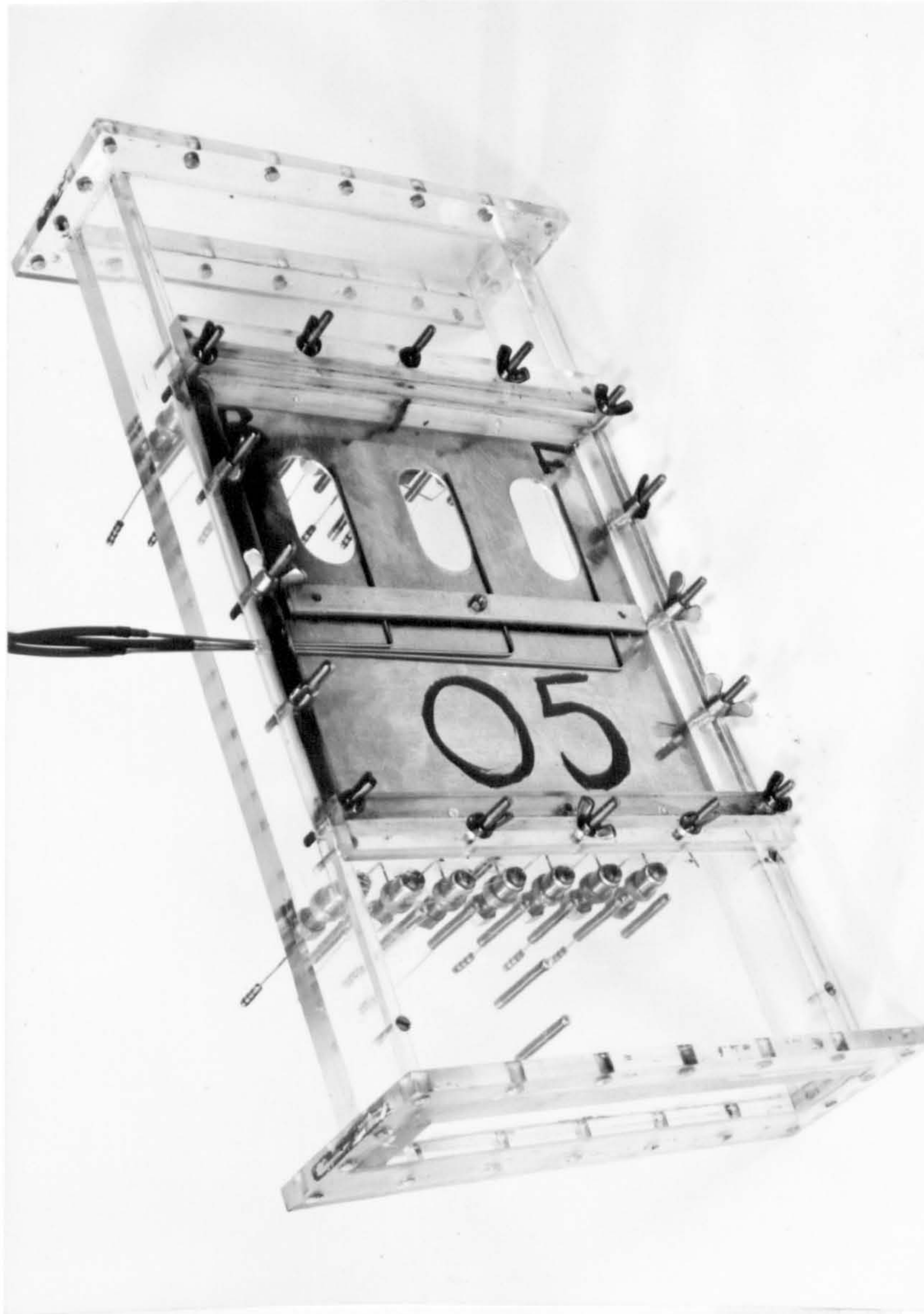


Plate 6

TEST SECTION COMPLETE

Perspex frame assembled with test section,
test plate in position.

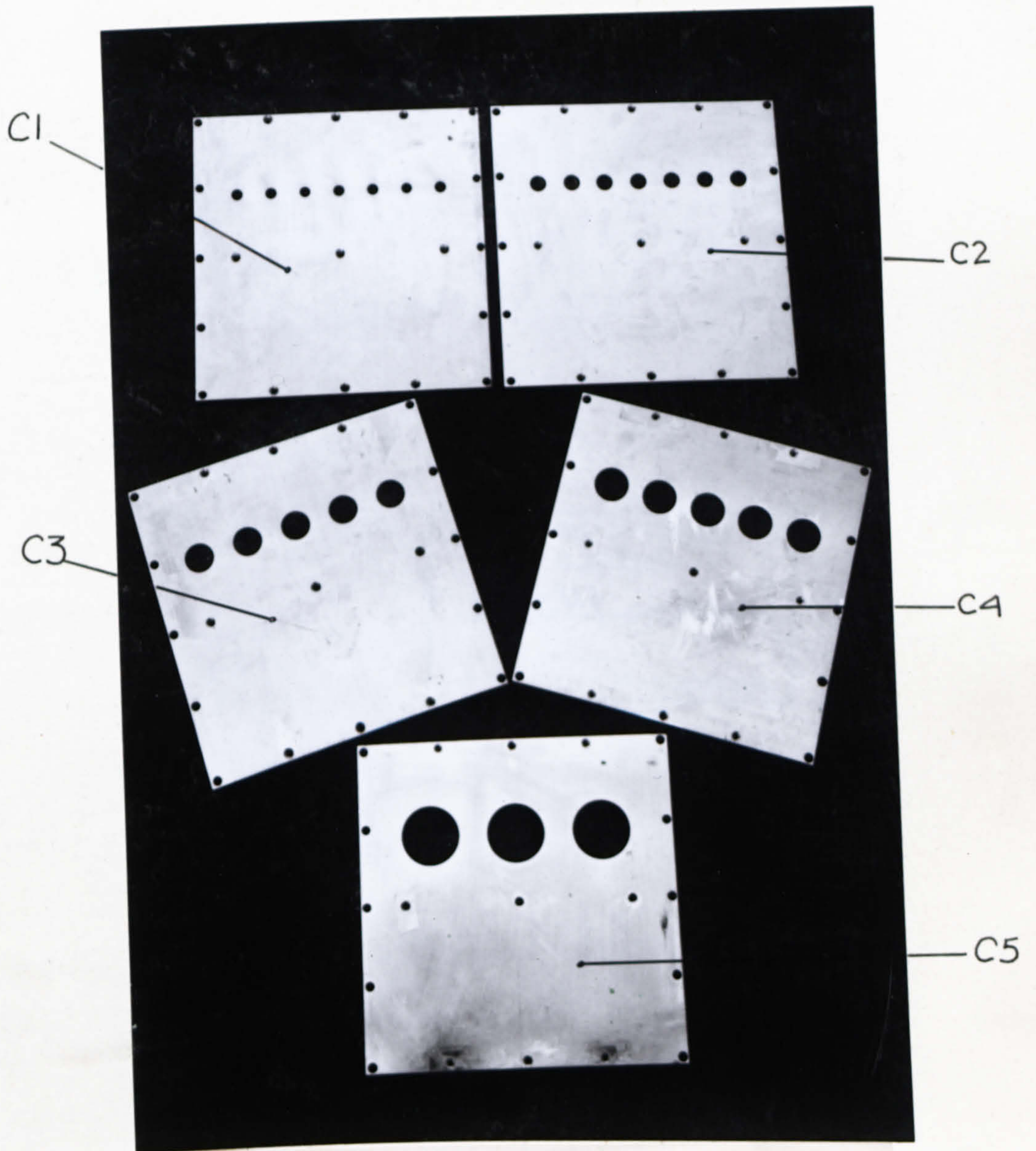


Plate 7

TEST HOLES CONFIGURATIONS

(i) Circular holes

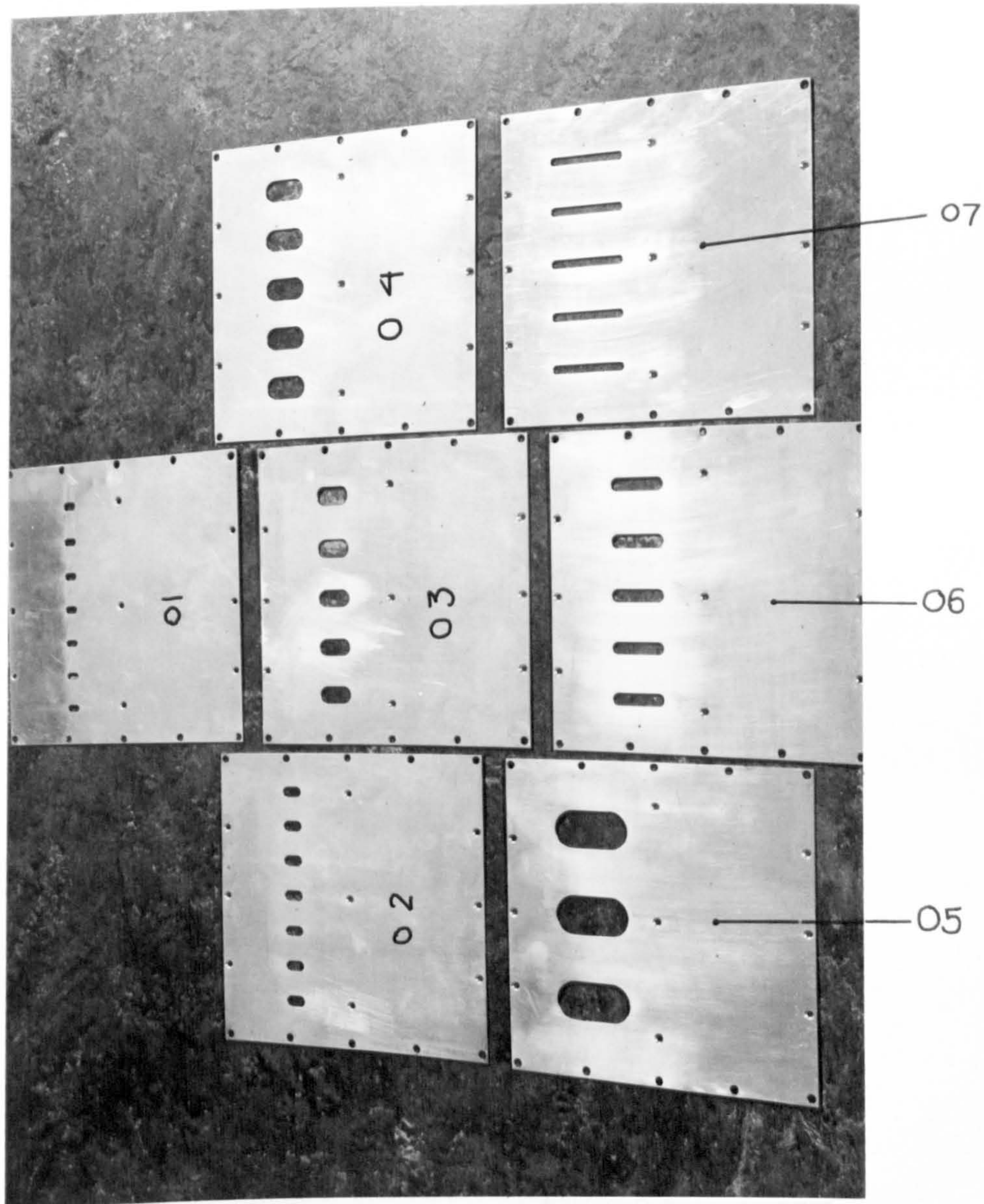


Plate 8

TEST HOLES CONFIGURATIONS

(ii) Oval slots

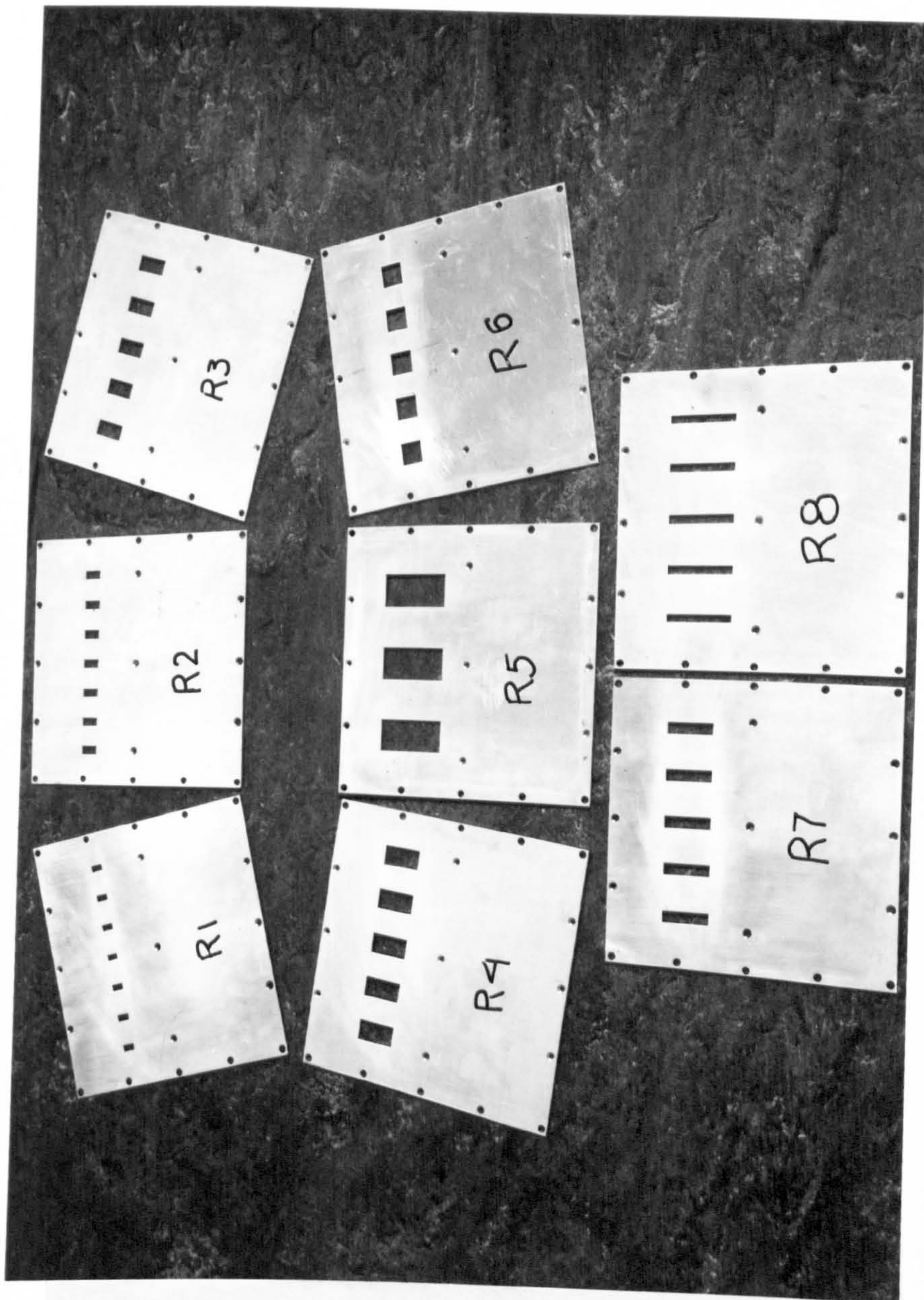


Plate 9

TEST HOLES CONFIGURATIONS

(iii) Rectangular slots



Plate 10

DEFLECTION ANGLE MEASUREMENT

Edge of the bevelled protractor lies along
jet core centre line.



Plate 11

JET DEFLECTION MEASUREMENT MECHANISM

Pointer moves freely around the axis, $\frac{1}{8}$ inch below and parallel to plate surface, deflector $1 \times \frac{3}{8}$ inch, 41 s.w.g. (.004" thick), and lies within jet potential core, and balanced w.r. to the axis.

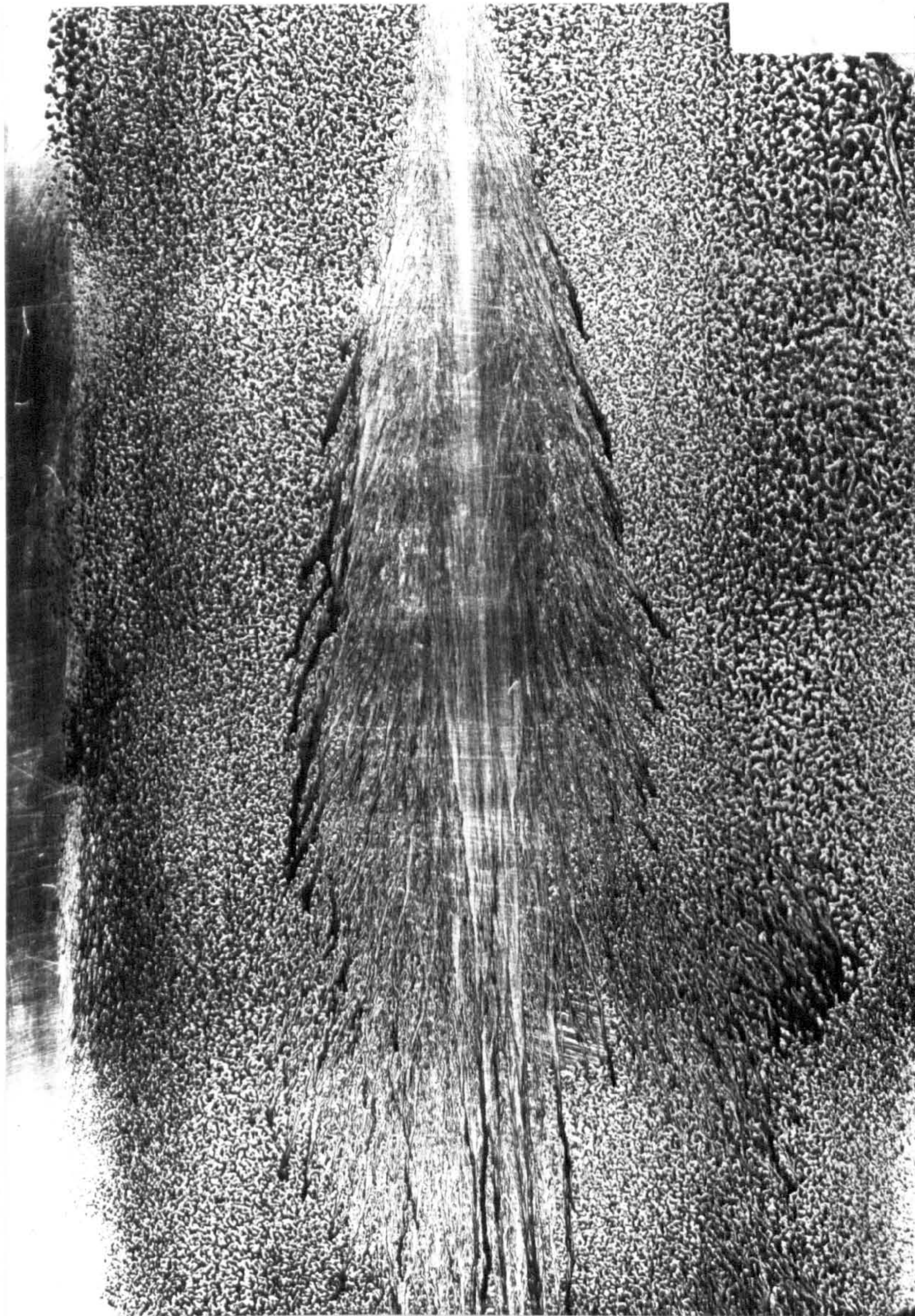


PLATE 12

Jet profile for circular holes

Hole C_1 - No Cross Flow

$\theta = 85^\circ$

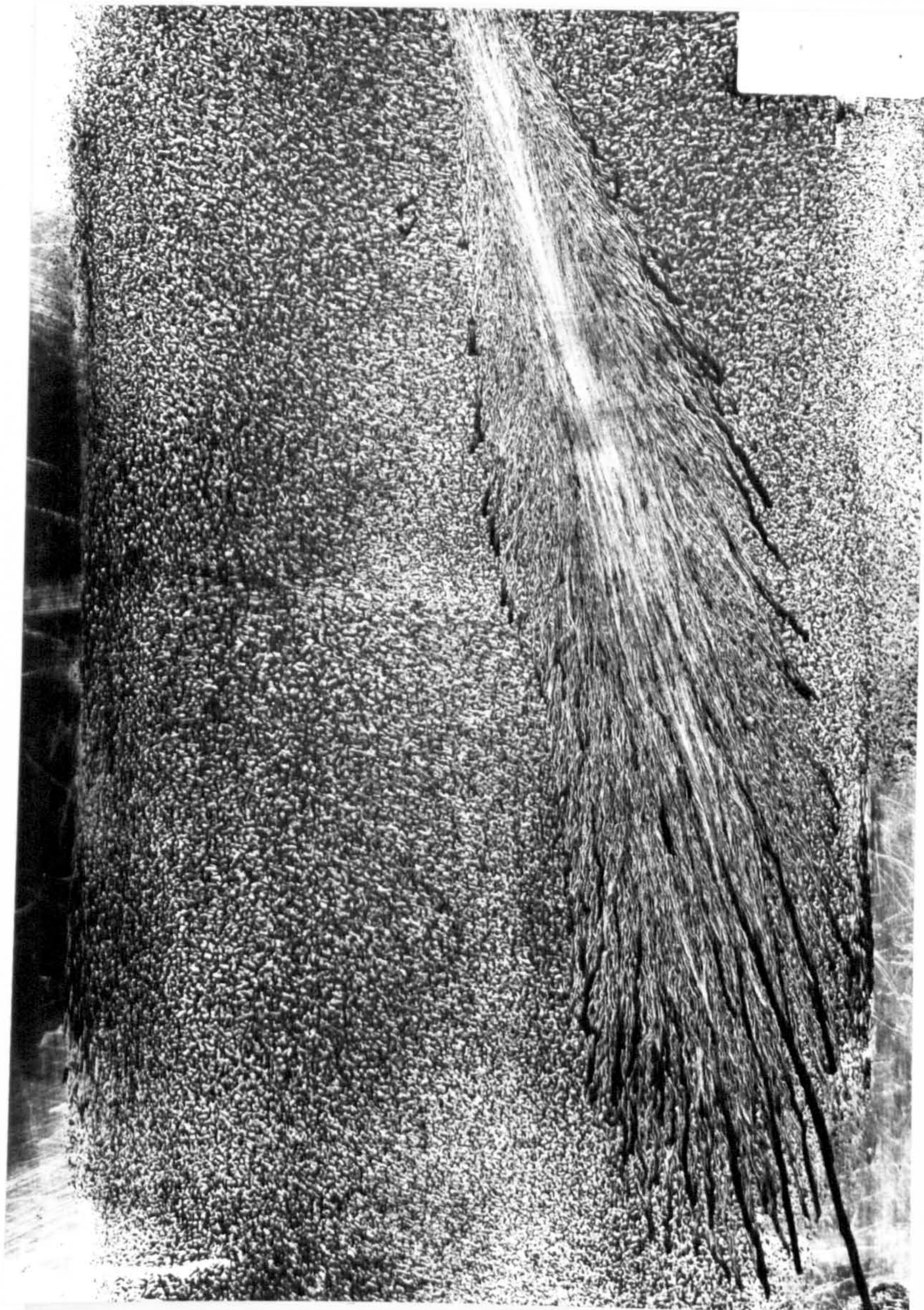


PLATE 13

Jet profile for circular holes

Hole C_1 - $V_1 = 80$ ft./sec.

$= 73^\circ$

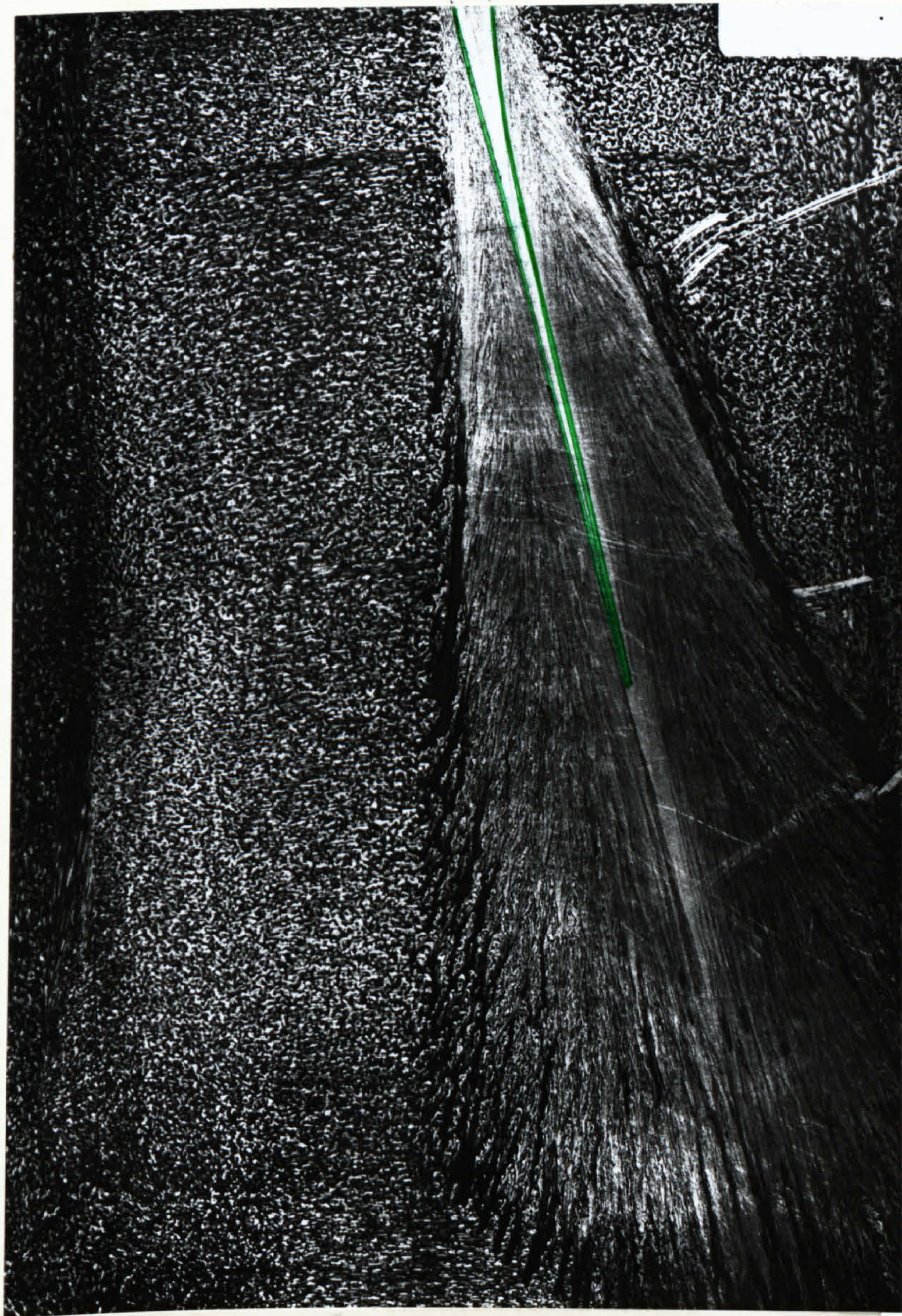


PLATE 14

Jet profile for circular holes

Hole C2 - $V_1 = 130 \text{ ft./sec.}$

$= 76^\circ$

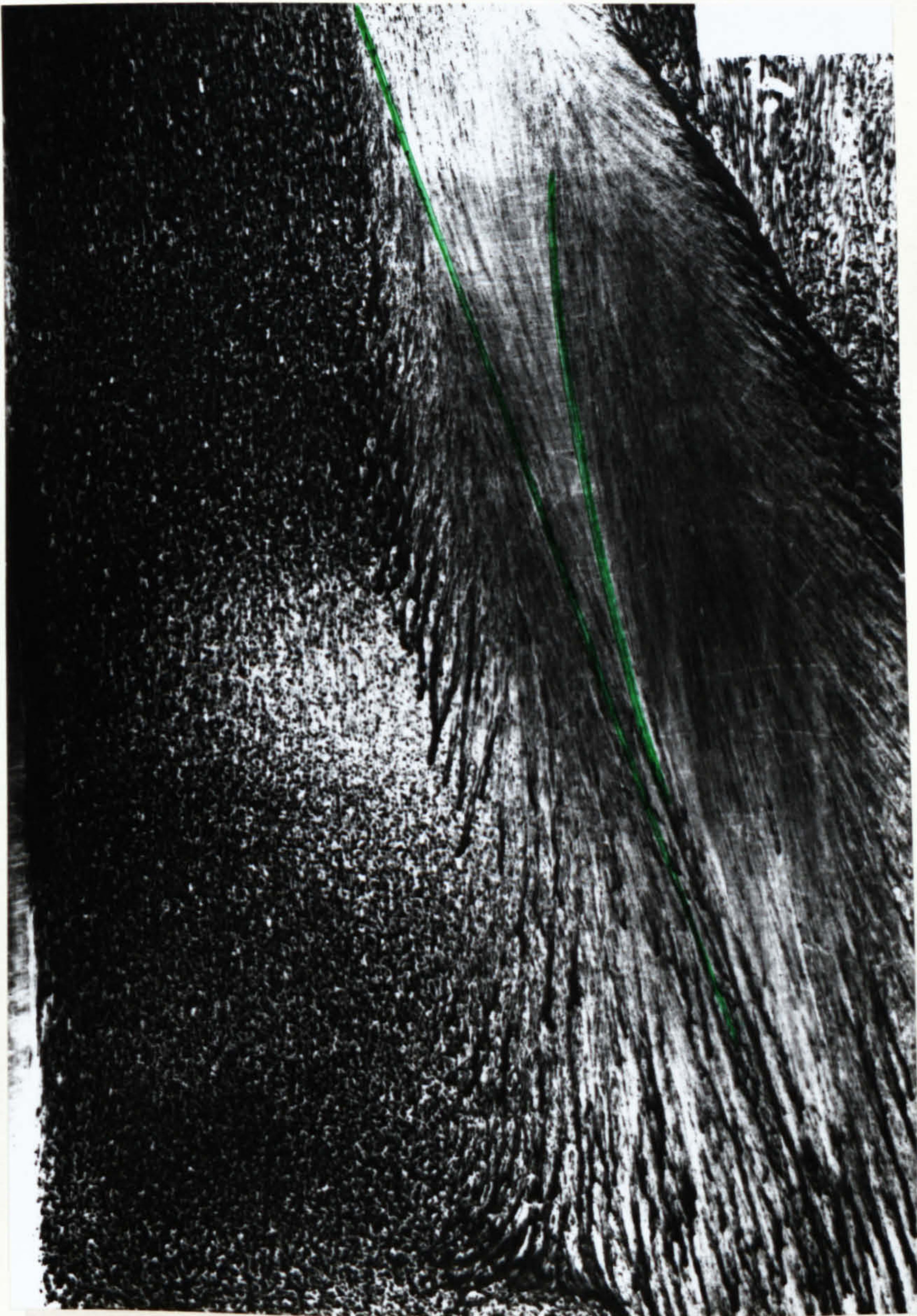


PLATE 15

Jet profile for circular holes

Hole C5 - No cross flow

$$\theta = 76^{\circ}$$



PLATE 16

Jet profile for circular holes

Hole C5 - $V_1 = 130 \text{ ft./sec.}$

$= 76^\circ$

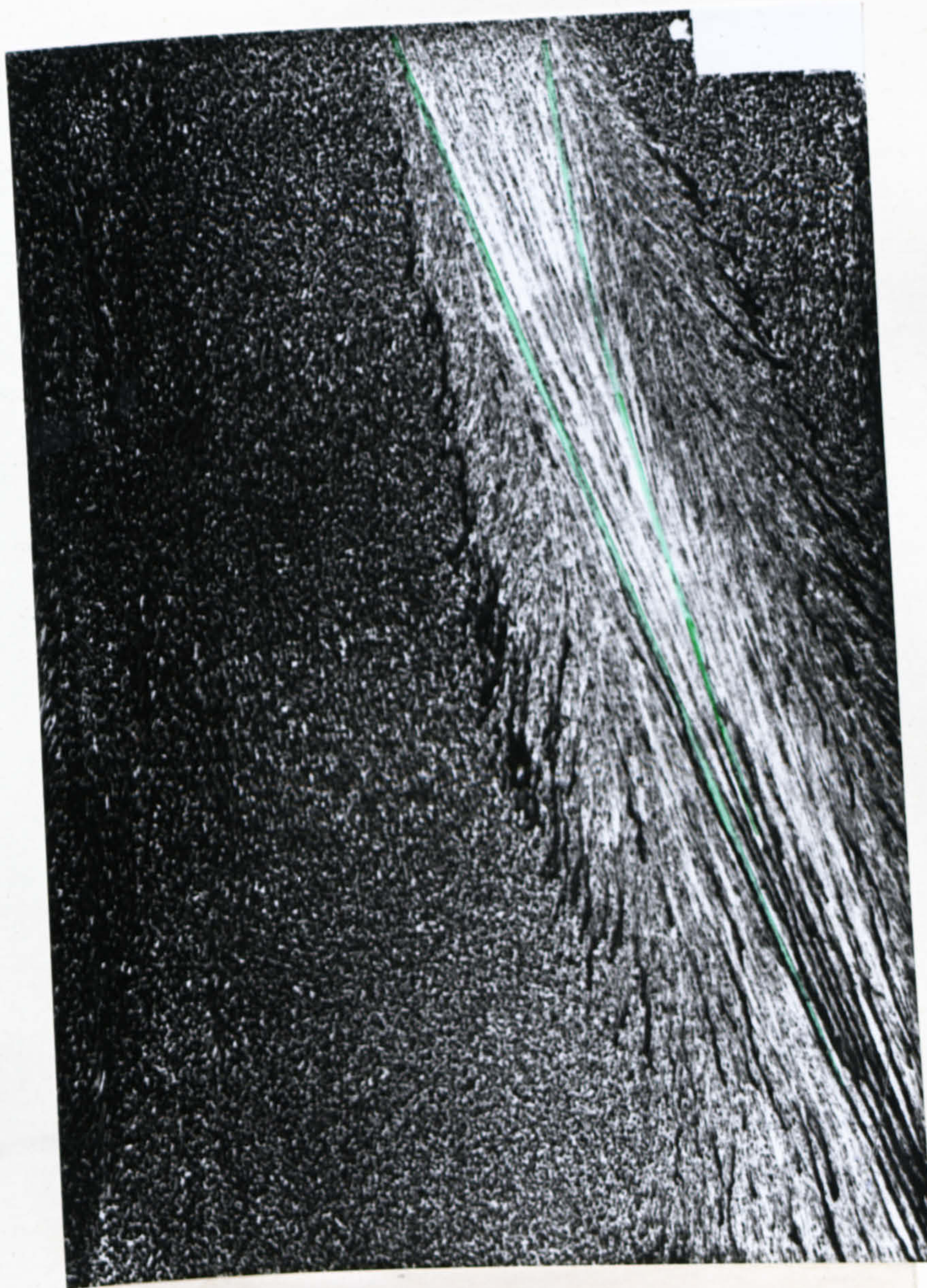


PLATE 17

Jet profile for circular holes

Hole C5 - $V_1 = 130 \text{ ft./sec.}$

$= 73^\circ$

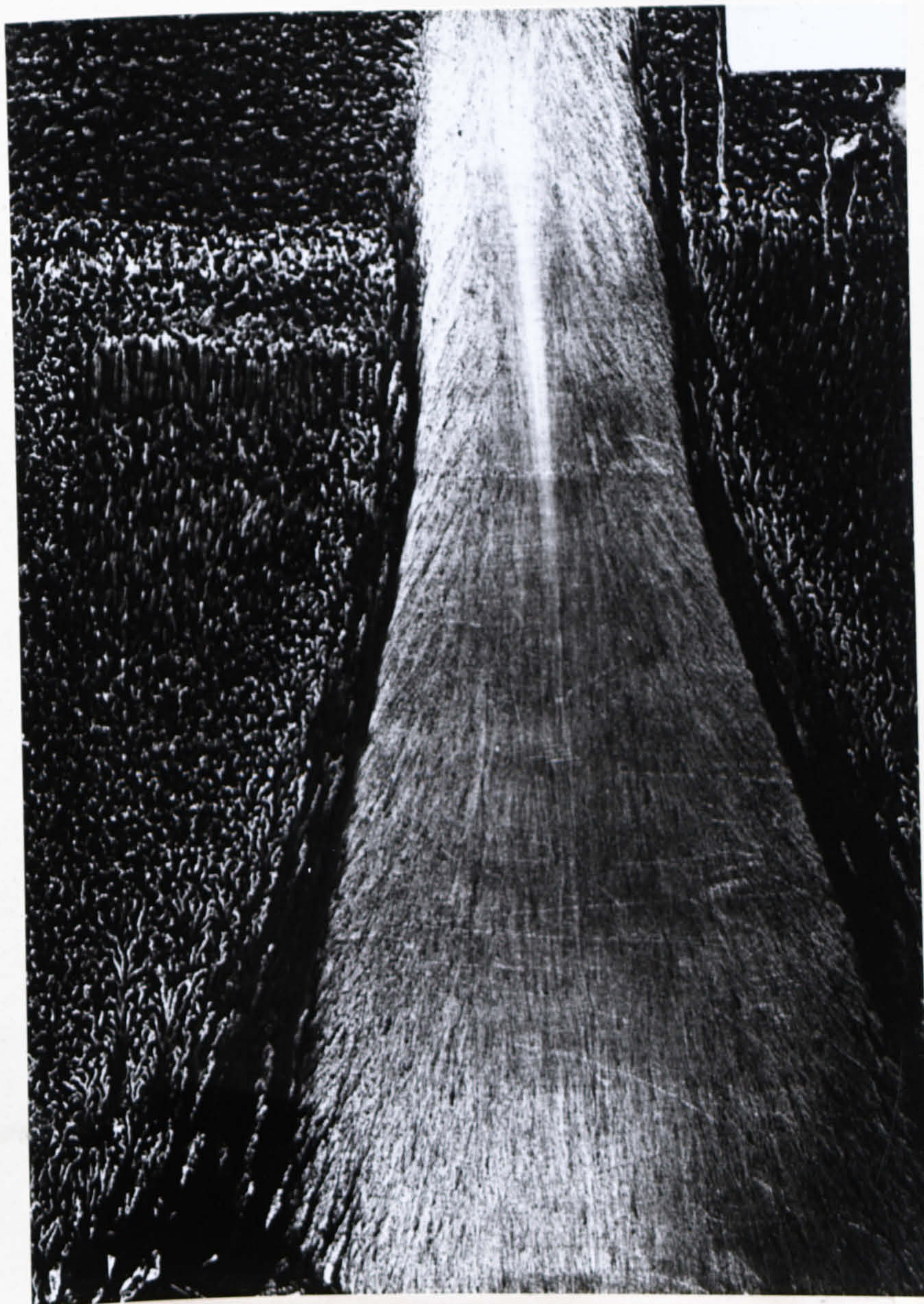
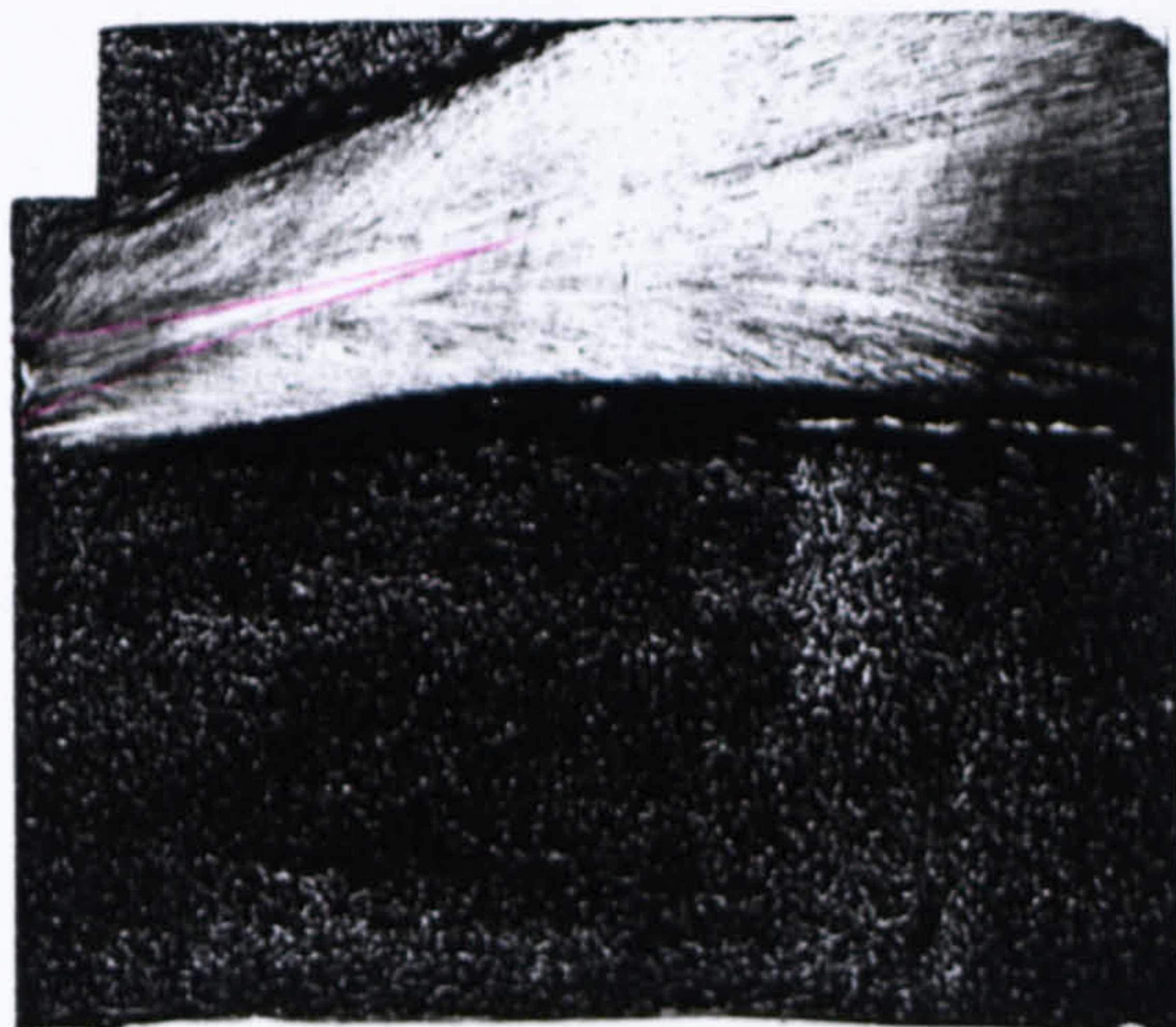


PLATE 18

Jet profile for oval slots

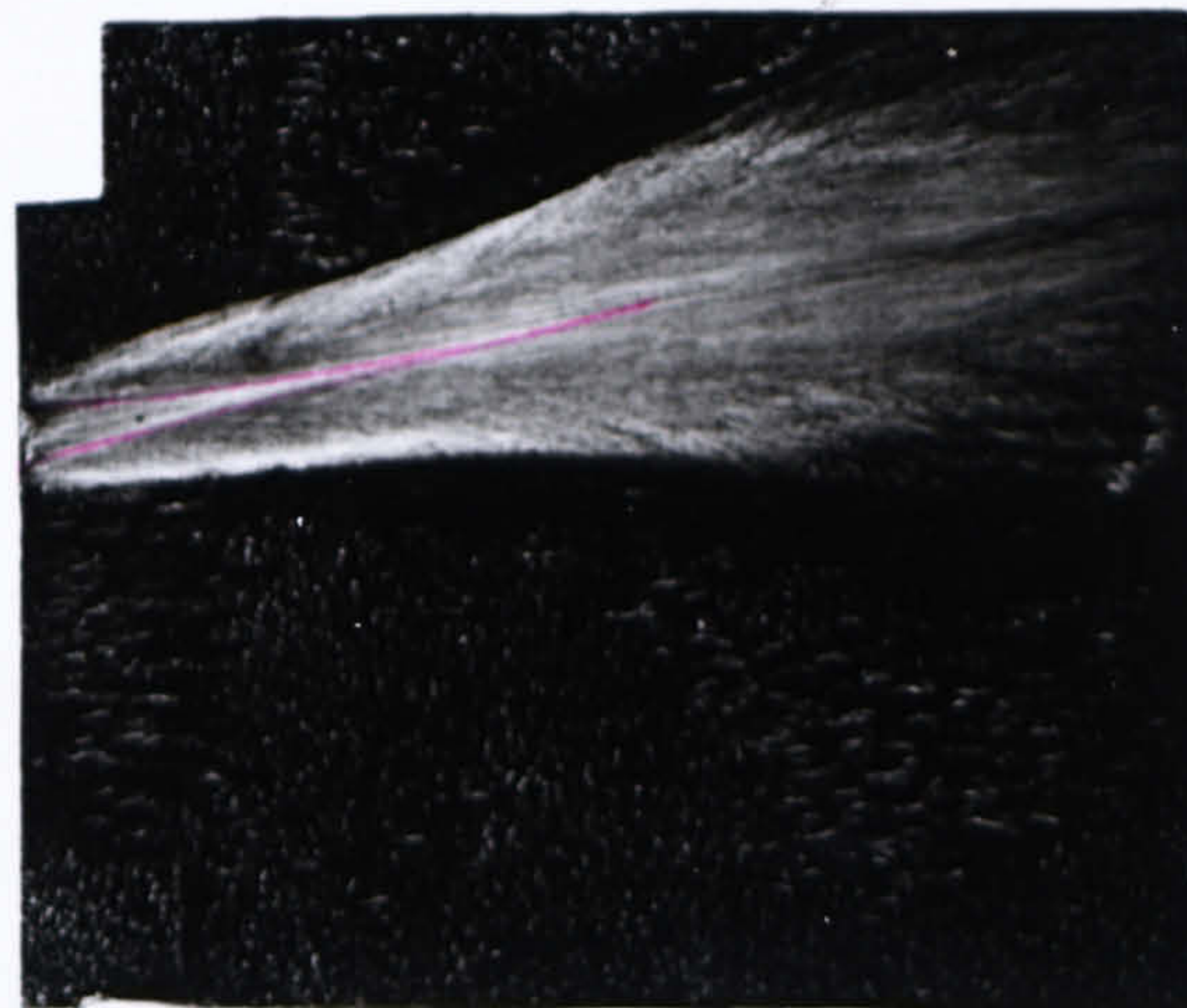
Slot 02 - No Cross Flow

$$\theta = 84^\circ$$



$$V_1 = 130 \frac{\text{ft}}{\text{sec}}$$

$$\phi = 71^\circ$$



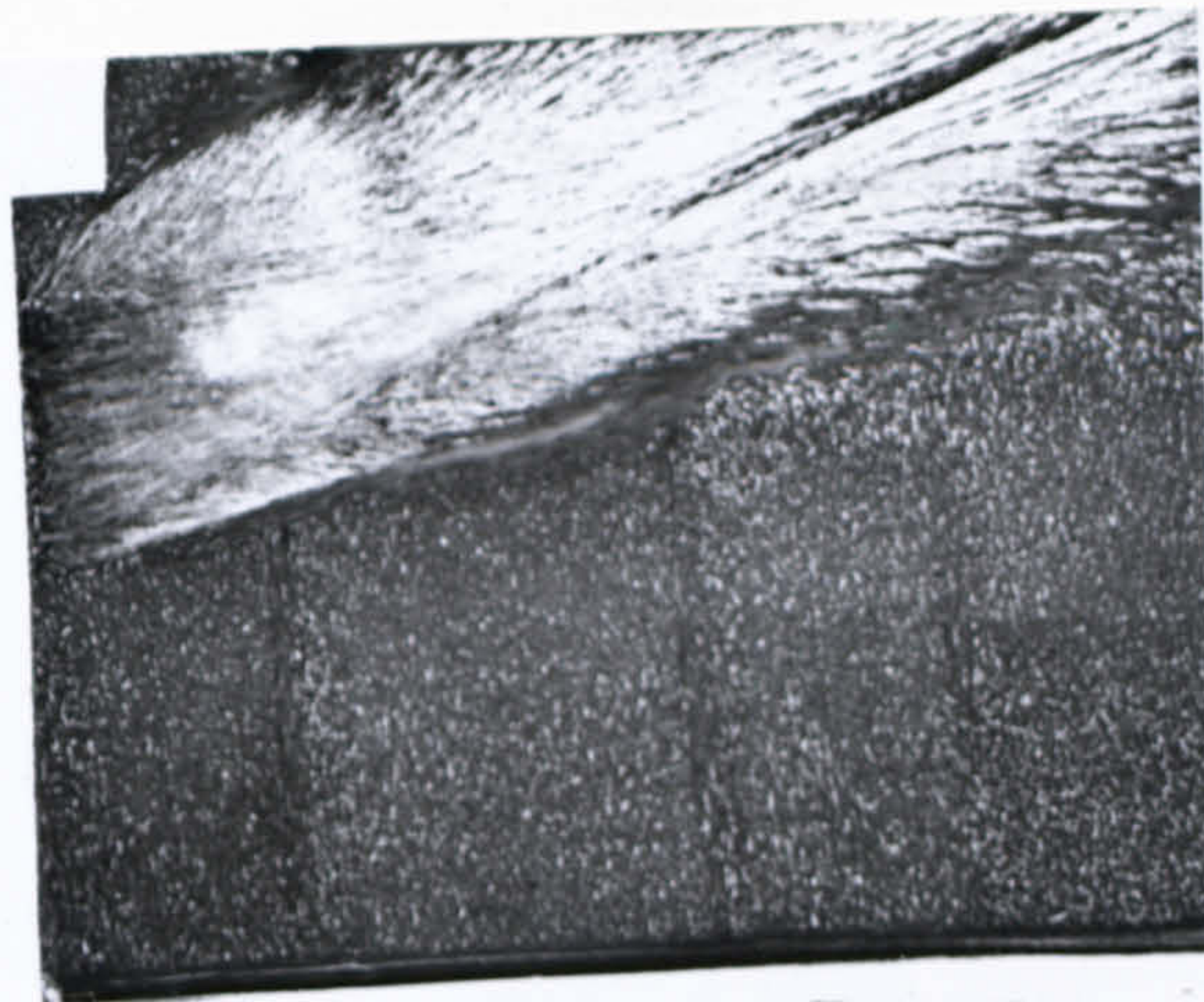
$$V_1 = 80 \frac{\text{ft}}{\text{sec}}$$

$$\phi = 82^\circ$$

PLATE 19

Jet profile for oval slots

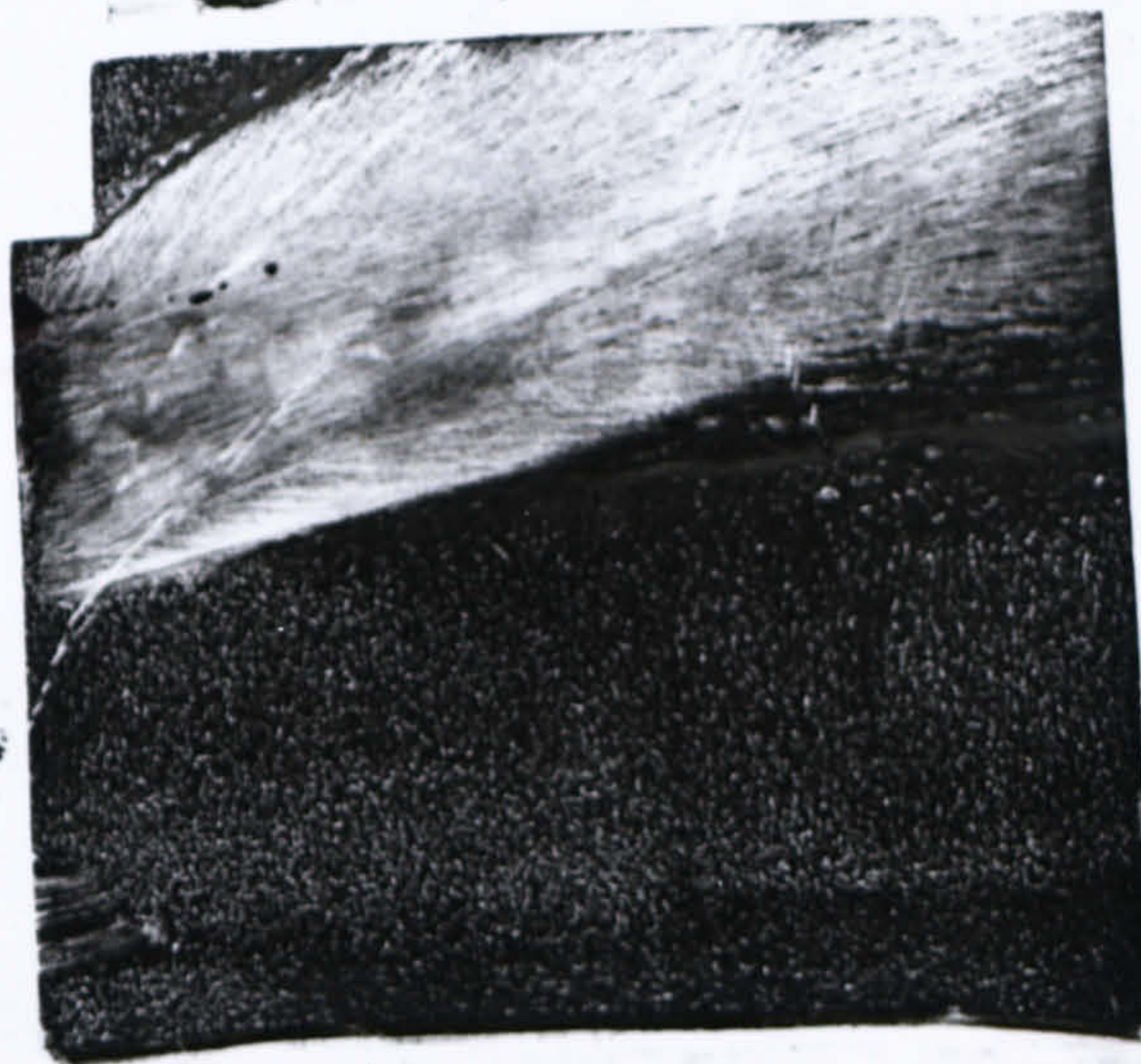
Slot 02



$$V_1 = 130 \frac{\text{ft}}{\text{sec}}$$

$$\Phi = 72^\circ$$

NO 130



$$V_1 = 80 \frac{\text{ft}}{\text{sec}}$$

$$\Phi = 77^\circ$$

0506

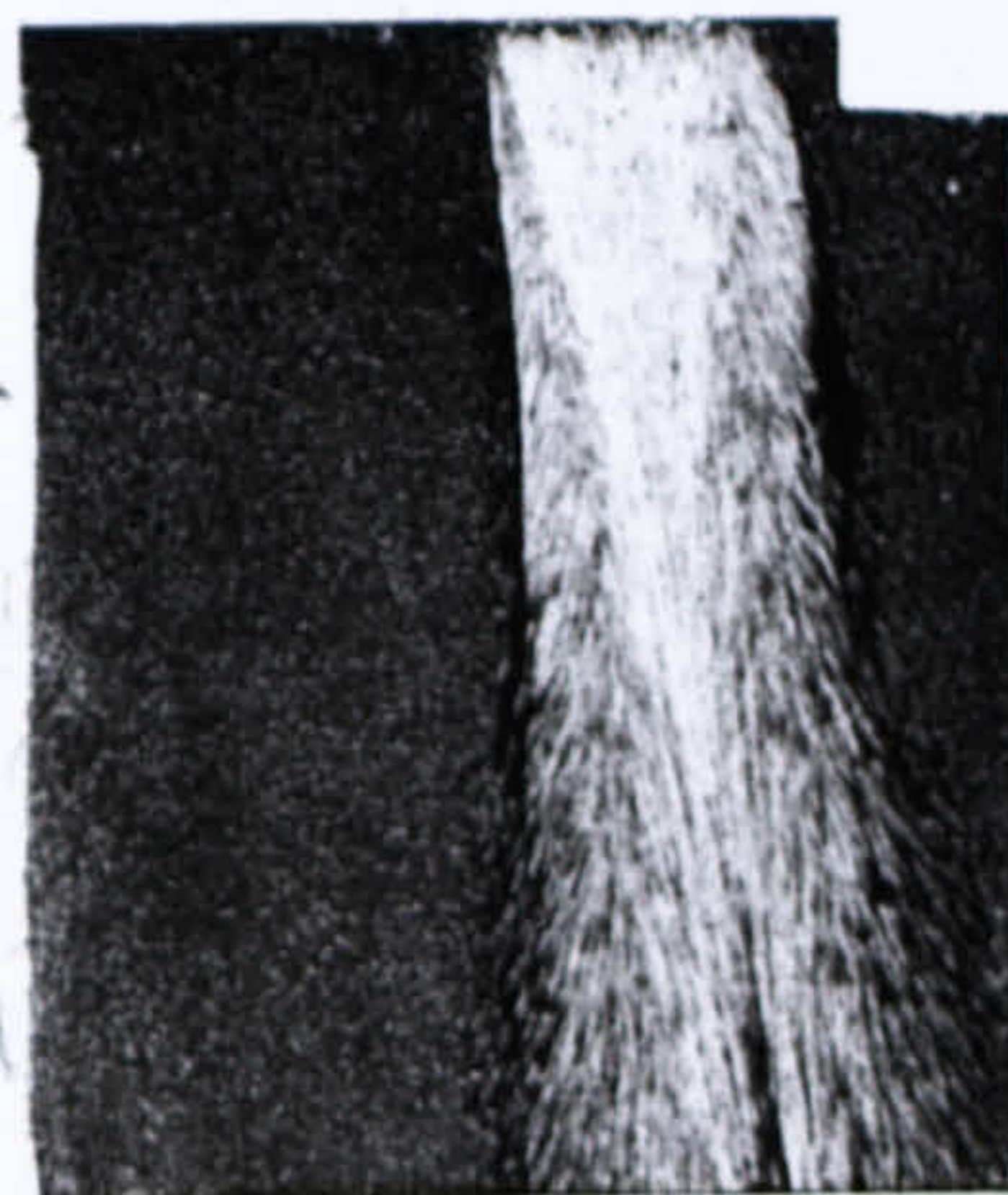
PLATE 20

Jet profile for oval slots

Slot 05

NO CROSS FLOW

$$\Phi_0 = 85^\circ$$



APPROACH velocity = $80 \frac{\text{ft}}{\text{sec}}$

$$\Phi = 80^\circ$$



APPROACH velocity = $130 \frac{\text{ft}}{\text{sec}}$

$$\Phi = 75^\circ$$

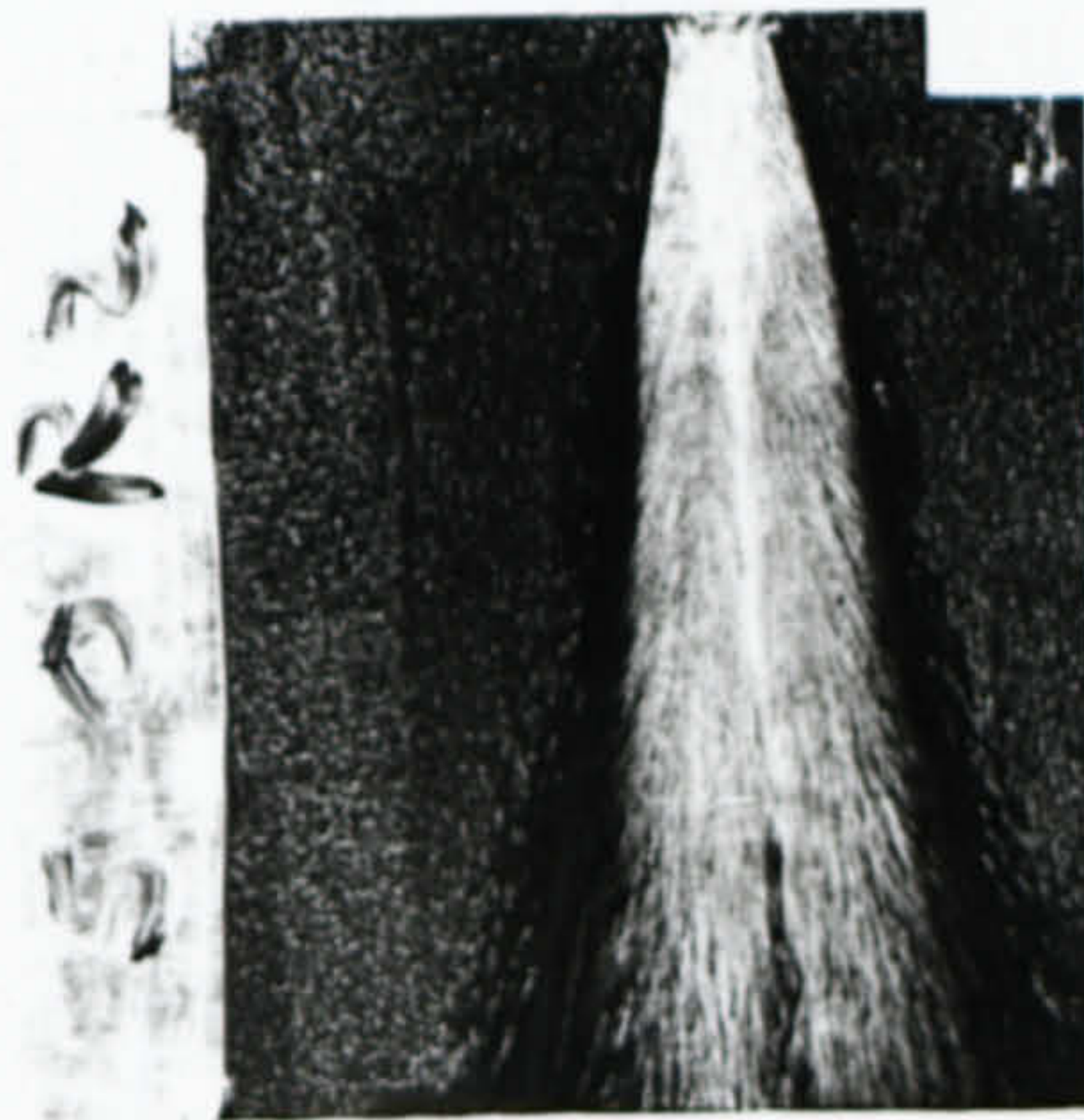
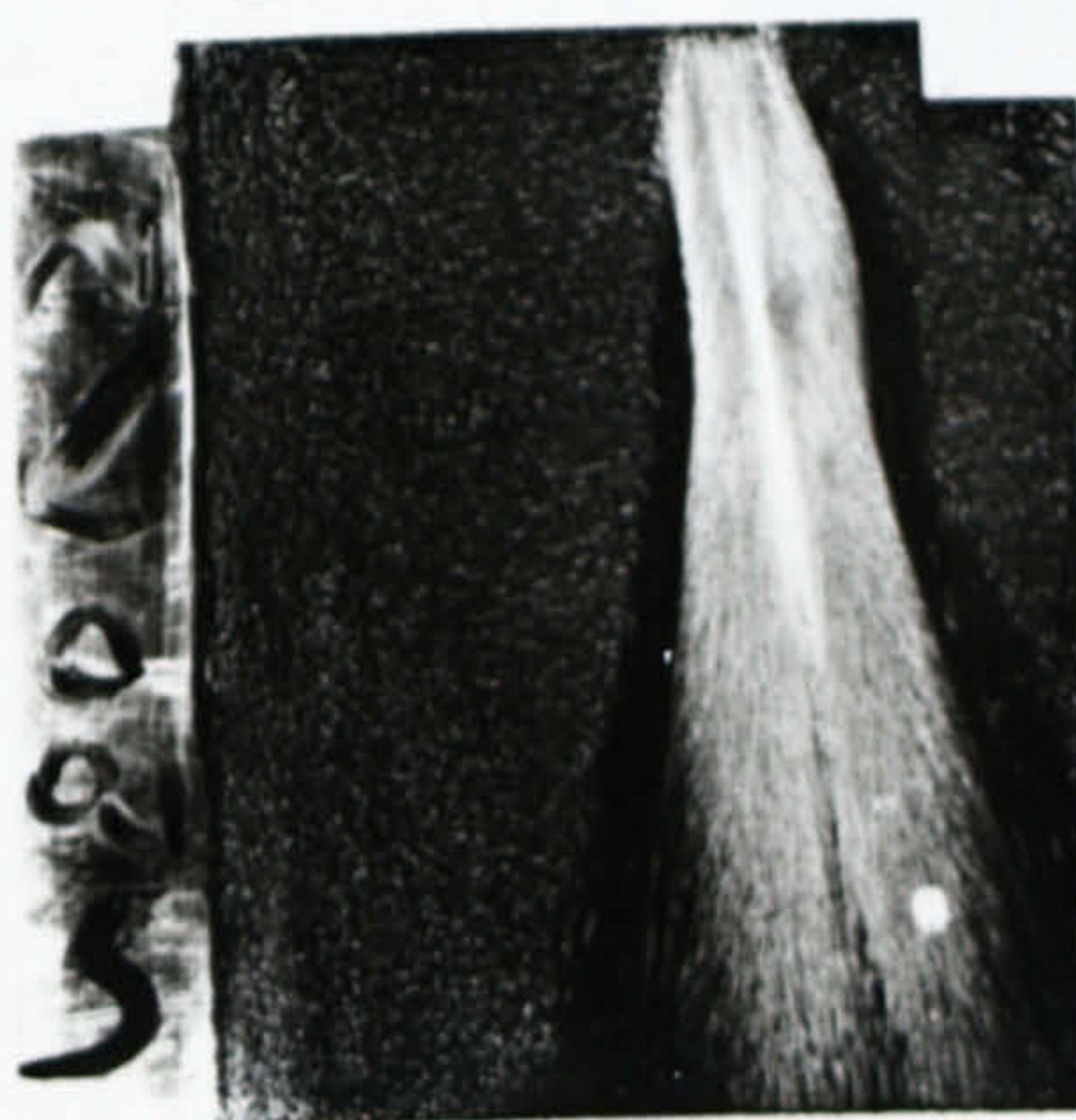
PLATE 21

Jet profile for oval slots

Slot 07

NO CROSSFLOW

$$\phi_0 = 82^\circ$$



APPROACH velocity = $80 \frac{\text{ft}}{\text{sec}}$

$$\phi = 75^\circ$$



APPROACH velocity = $130 \frac{\text{ft}}{\text{sec}}$

$$\phi = 71^\circ$$

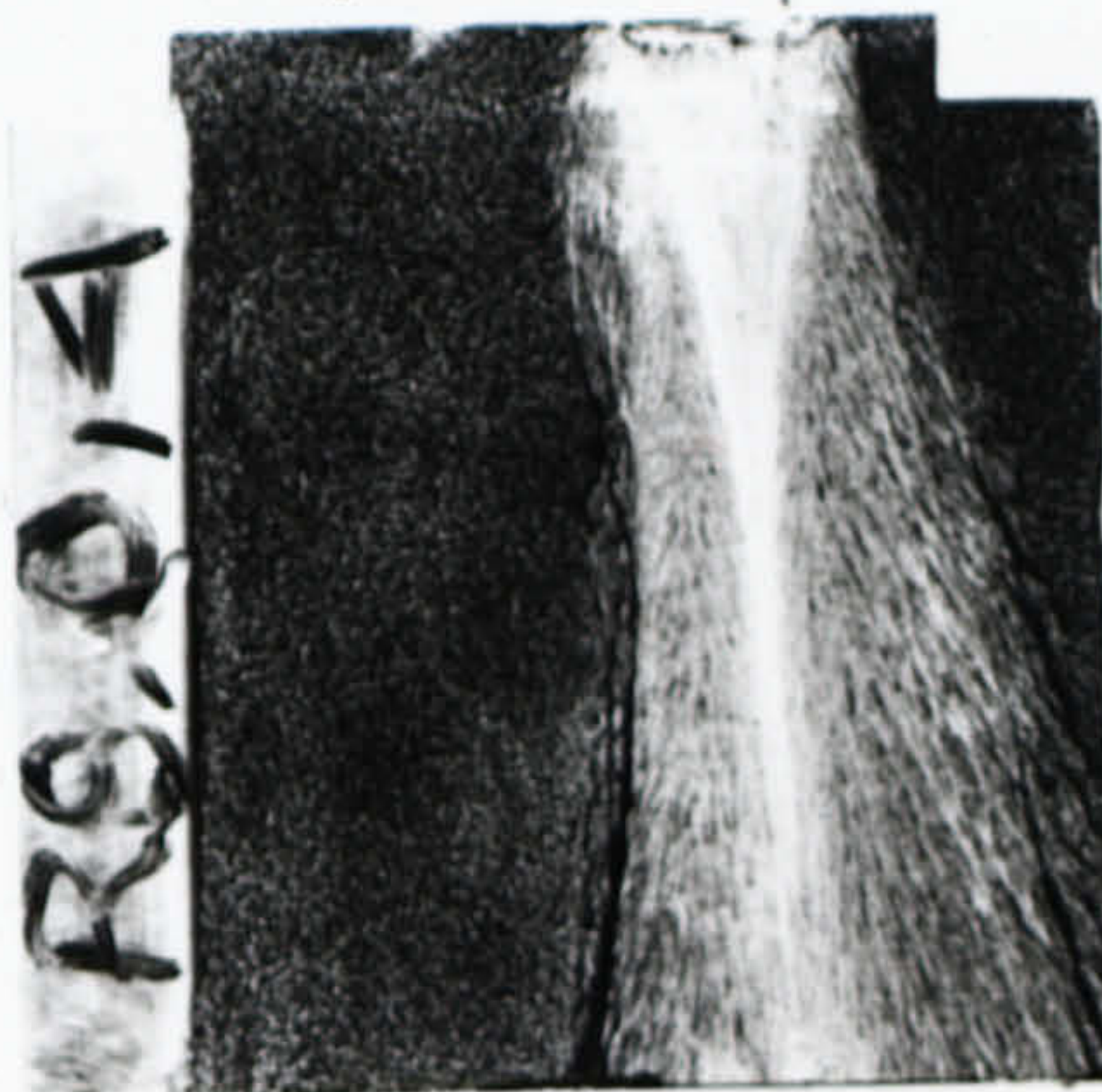
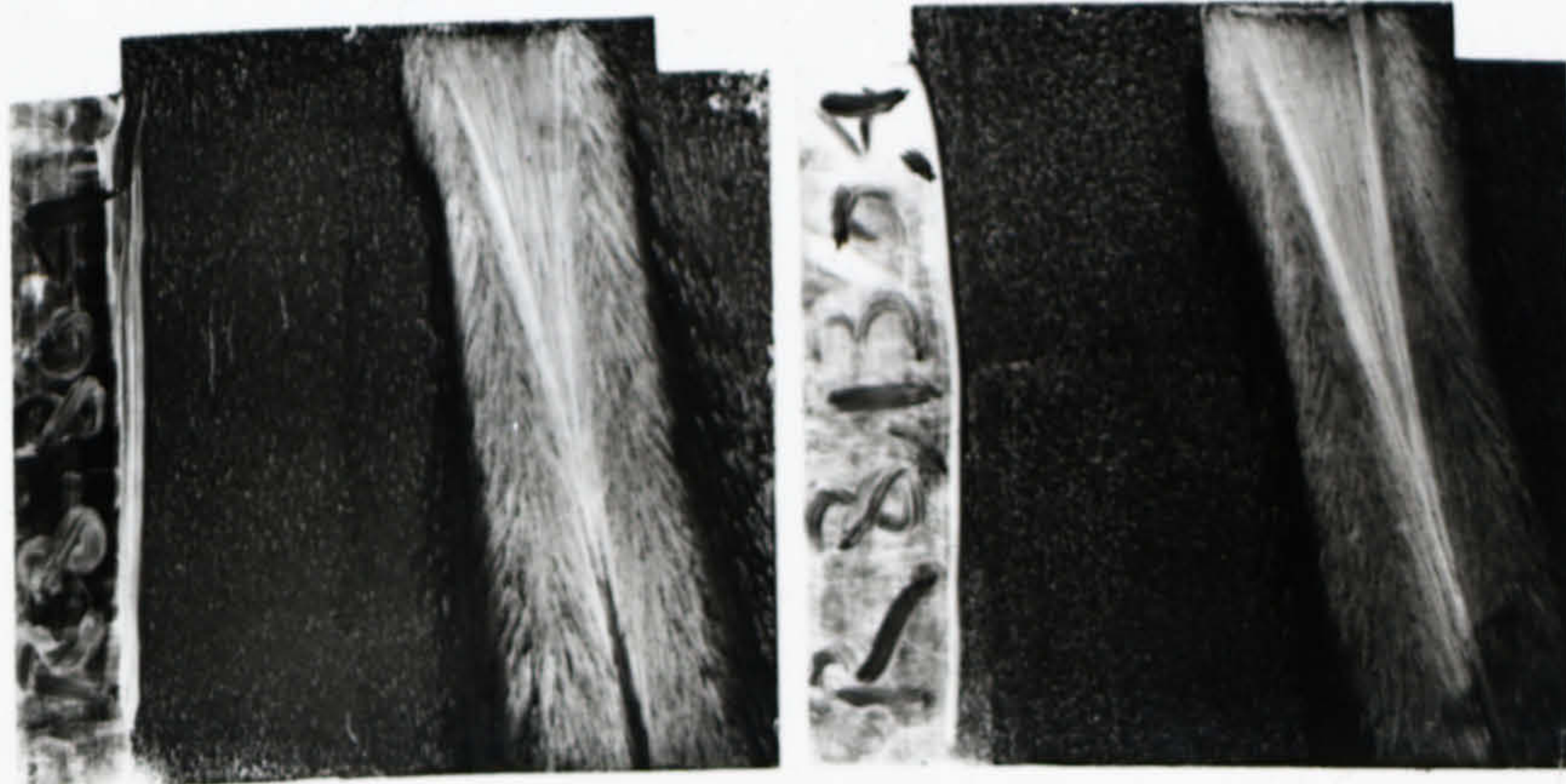
PLATE 22

Jet profile for rectangular slots

Slot R2

NO CROSS FLOW

$$\Phi_0 = 85^\circ$$



APPROACH VELOCITY = $80 \frac{\text{ft}}{\text{sec}}$

APPROACH VELOCITY = $130 \frac{\text{ft}}{\text{sec}}$

$$\Phi = 80^\circ$$

$$\Phi = 76^\circ$$

PLATE 23

Jet profile for rectangular slots

Slot R8

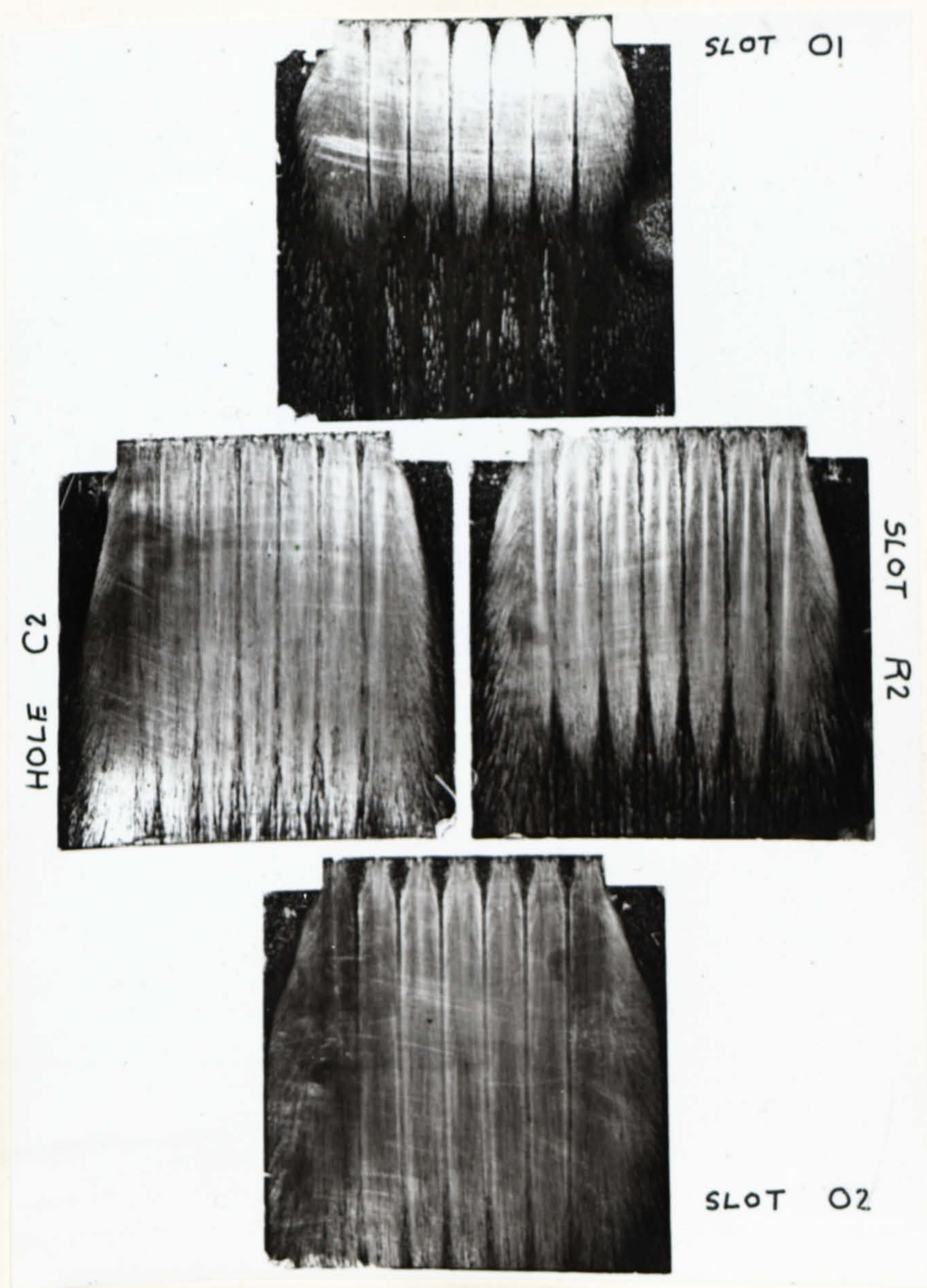


PLATE 24

Jet profile for liner holes

$$p_1/p_j = 1.10 - V_1 = 80 \text{ ft./sec.}$$