UNCLASSIFIED

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES
3 4456 0350476 8

ORNL-2301
Chemistry-General cy. 4

HYDRAULIC CYCLONES FOR APPLICATION TO HOMOGENEOUS REACTOR CHEMICAL PROCESSING

P. A. Haas

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION

LIBRARY LOAN COPY

DO NOT TRANSFER TO ANOTHER PERSON

If you wish someone else to see this document, send in name with document and the library will arrange a loan.

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation
UCC
POST OFFICE BOX X · OAK RIDGE, TENNESSEE

UNCLASSIFIED

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

Report Number: ORNL-2301

Contract No. W-7405, eng 26

CHEMICAL TECHNOLOGY DIVISION

Unit Operations Section

HYDRAULIC CYCLONES FOR APPLICATION TO HOMOGENEOUS REACTOR CHEMICAL PROCESSING

P. A. Haas

Work by: J. R. Engel
P. A. Haas
E. O. Nurmi
M. E. Whatley

DATE ISSUED:
NOV 18 1957

OAK RIDGE NATIONAL LABORATORY
Operated by
UNION CARBIDE NUCLEAR COMPANY
A Division of
UNION CARBIDE AND CARBON CORPORATION
Post Office Box X
Oak Ridge, Tennessee

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0350476 8

INTERNAL DISTRIBUTION

1. C. E. Center
2. Biology Library
3. Health Physics Library
5. Central Research Library
6. Reactor Experimental Engineering Library
7-26. Laboratory Records Department
27. Laboratory Records, ORNL R.C.
28. A. M. Weinberg
29. L. B. Emlet (K-25)
30. J. P. Murray (Y-12)
31. J. A. Swartout
32. E. H. Taylor
33. E. D. Shipley
34-35. F. L. Culler
36. M. L. Nelson
37. W. H. Jordan
38. C. P. Keim
39. J. H. Frye, Jr.
40. S. C. Lind
41. A. H. Snell
42. A. Hollaender
43. K. Z. Morgan
44. M. T. Kelley
45. T. A. Lincoln
46. R. S. Livingston
47. A. S. Householder
48. C. S. Harrill
49. C. E. Winters
50. D. W. Cardwell
51. D. Phillips
52. W. K. Eister
53. F. R. Bruce
54. D. E. Ferguson
55. R. B. Lindauer
56. H. E. Goeller
57. R. A. Charpie
58. J. A. Lane
59. M. J. Skinner
60. R. E. Blanco
61. G. E. Boyd
62. W. E. Unger
63. R. R. Dickison
64. A. T. Gresky
65. E. D. Arnold
66. C. E. Guthrie
67. J. W. Ullmann
68. K. B. Brown
69. K. O. Johnsson
70. H. M. McLeod
71. C. W. Hancher
72. J. C. Bresee
73. P. A. Haas
74. J. R. Engel
75. E. O. Nurmi
76. M. E. Whatley
77. W. W. Weinrich (consultant)
78. M. D. Peterson (consultant)
79. D. L. Katz (consultant)
80. G. T. Seaborg (consultant)
81. M. Benedict (consultant)
82. C. E. Larson (consultant)
83. L. Squires (consultant)
84. J. H. Rushton (consultant)
85. ORNL - Y-12 Technical Library, Document Reference Section

EXTERNAL DISTRIBUTION

86. R. F. Bacher, California Institute of Technology
87. Division of Research and Development, AEC, ORO
88-527. Given distribution as shown in TID-4500 (13th ed.) under Chemistry-General category

CONTENTS

		Page
1.0	ABSTRACT	1
2.0	INTRODUCTION	1
3.0	RELATION BETWEEN DIMENSIONS AND PERFORMANCE	2
	3.1 Particle Efficiency from Hydroclone Size	2
	3.2 Optimum Hydroclone Dimension Ratios	6
	3.3 Correlation of Flow Capacities	8
4.0	HEAVY-PHASE ACCUMULATION WITH INDUCED UNDERFLOW OPERATION	9
	4.1 Concept of Induced Underflow Operation	9
	4.2 Determination of Induced Underflow Ratio	11
	4.3 Predicted Performance Including Concentration Factors	15
5.0	DESIGN FEATURES FOR HOMOGENEOUS REACTOR CHEMICAL PROCESSING	22
	5.1 Corrosion and Materials of Construction	22
	5.2 Remote Maintenance Requirements	22
	5.3 Operating Flexibility	22
6.0	PREDICTED PERFORMANCE OF HRT HYDROCLONES	25
7.0	REFERENCES	36

1.0 ABSTRACT*

Results are reported for studies of application of liquid cyclones, or hydroclones, to removal of 1 to 10-micron particles from aqueous streams. Optimum dimensions were determined, and 0.25 and 0.40-in. dia units were found to have capacities of 0.2 and 0.5 gpm for 80-ft liquid pressure drops. Under these conditions, hydroclones of these dimensions removed 50% or more of precipitated rare earth sulfates, ZrO_2, or iron oxides (sp. gr. 2.5-5) of 1-micron particle size from aqueous streams at 250-300°C. Results with 0.16, 0.25, 0.40, 0.50, and 0.56-in. dia hydroclones were used to extrapolate and test literature correlations of flow capacities and efficiencies. A method of batch underflow accumulation gave heavy-phase concentration factors of up to 4500. Titanium hydroclones were corroded at rates of 10 mils/year or less in uranyl sulfate solutions containing 10-300 g of uranium per kilogram of H_2O at 250-300°C. Performance curves were calculated for three sizes of hydroclones designed for use in the Homogeneous Reactor Test Chemical Processing Plant.

2.0 INTRODUCTION

The use of hydraulic cyclones, or hydroclones, in removing 1-micron solid particles from aqueous solutions was studied. A simple, durable, liquid-solid separation apparatus was needed to remove precipitated fission and corrosion products from uranyl sulfate solutions used in aqueous homogeneous reactors. Removal of 1-micron particles required hydroclones of less than 1 in. dia, and experiments were limited to 0.16, 0.25, 0.40, 0.50, and 0.56-in.-dia units. The results were intended to permit selection of both optimum hydroclone units and optimum operating procedures for the proposed reactor applications.

The use of liquid-solid separators was suggested by the low solubility of some fission products in uranyl sulfate solutions at the high temperature of the reactor operation.[1] Solubilities of many contaminants of reactor fluid streams are in the range 3-50 ppm at 250 to 300°C. These include iron oxides and ZrO_2 in water, and iron oxides, ZrO_2, rare earth sulfates, and some other fission products in uranyl sulfate solutions. Complete removal of the insoluble and the gaseous fission products would represent removal of over 80% of the fission products poisons. Combination of liquid-solid separation and gas removal methods could thus reduce, and perhaps completely replace, other methods of processing aqueous solution fuels. Removal of insoluble corrosion products from aqueous coolants is another possible application of hydroclones to reactor systems.

---

* The material in Secs. 2, 3, and 5 was presented at the 2nd Annual American Nuclear Society Meeting, June 7, 1956, and published as "Midget Hydroclones Remove Micron Particles", Chem. Engr. Prog. 53: 203-207 (1957).

In a hydroclone, the centrifugal field caused by the high velocity of fluid entering on a tangent results in accumulation of the heavy phase at the walls. This can be withdrawn as an underflow stream. The feed port of a hydroclone is at the point of largest diameter (Fig. 1), which is used to identify the hydroclone size. The vortex finder, extending down into the hydroclone cavity, contains the overflow port, to which the hydroclone body tapers. Experimental work reported by several investigators[2-4] has determined the hydroclone flow patterns (Fig. 2). The fluid entering takes spiral paths downward. As the fluid moves toward the hydroclone center, at some point the vertical velocity reverses to a spiral path to the overflow port. A particle that is to be removed in the underflow stream must be accelerated by the centrifugal force to a velocity which keeps it out of the inner spiral to the overflow. Boundary flows apparently exist with such a flow at the top, resulting in a short circuit of fluid with little phase separation.

The major advantages of the liquid cyclone or hydroclone are simplicity, small size, high efficiency, and high capacity. Hydroclones can be easily designed to handle high-temperature and high-pressure fluid streams. Almost any material which will withstand the fluid processed can be used as the material of construction. The energy required for the separation process is obtained as a fluid pressure drop and can be supplied by a pump. As compared to a centrifuge or continuous filter, a hydroclone has no moving parts or mechanical seals, and avoids nearly all the difficult remote maintenance or cleaning problems associated with the use of centrifuges or filters on radioactive materials. The concentrated solids leave as a slurry stream.

The initial phase of the development studies reported were completed by M. E. Whatley in 1954. Other studies were made by J. R. Engel, E. O. Nurmi, and P. A. Haas. Technical assistance from many sources, particularly on particle size determinations by members of the Analytical Chemistry Division, is acknowledged.

3.0 RELATIONS BETWEEN DIMENSIONS AND PERFORMANCE

Studies were made to permit dimensioning of hydroclones to separate particles of 1-10 microns size, since precipitated rare earth sulfates and corrosion products in homogeneous reactor fuels are expected to be in this size range. Experimental work was limited to hydroclones between 0.16 and 0.56 in. dia. Efficiencies* for material containing 80 wt % particles between 0.6 and 3.0 microns dia ranged from 20 to 70%.

3.1 Optimum Hydroclone Dimensions

Optimum hydroclone dimensions for 0.25 and 0.40 in. dia units were determined with ThO_2 slurries. A constant pressure drop is the logical basis

* The hydroclone efficiency, E_1, is the fraction of the solid material in the feed stream which is discharged through the underflow port.

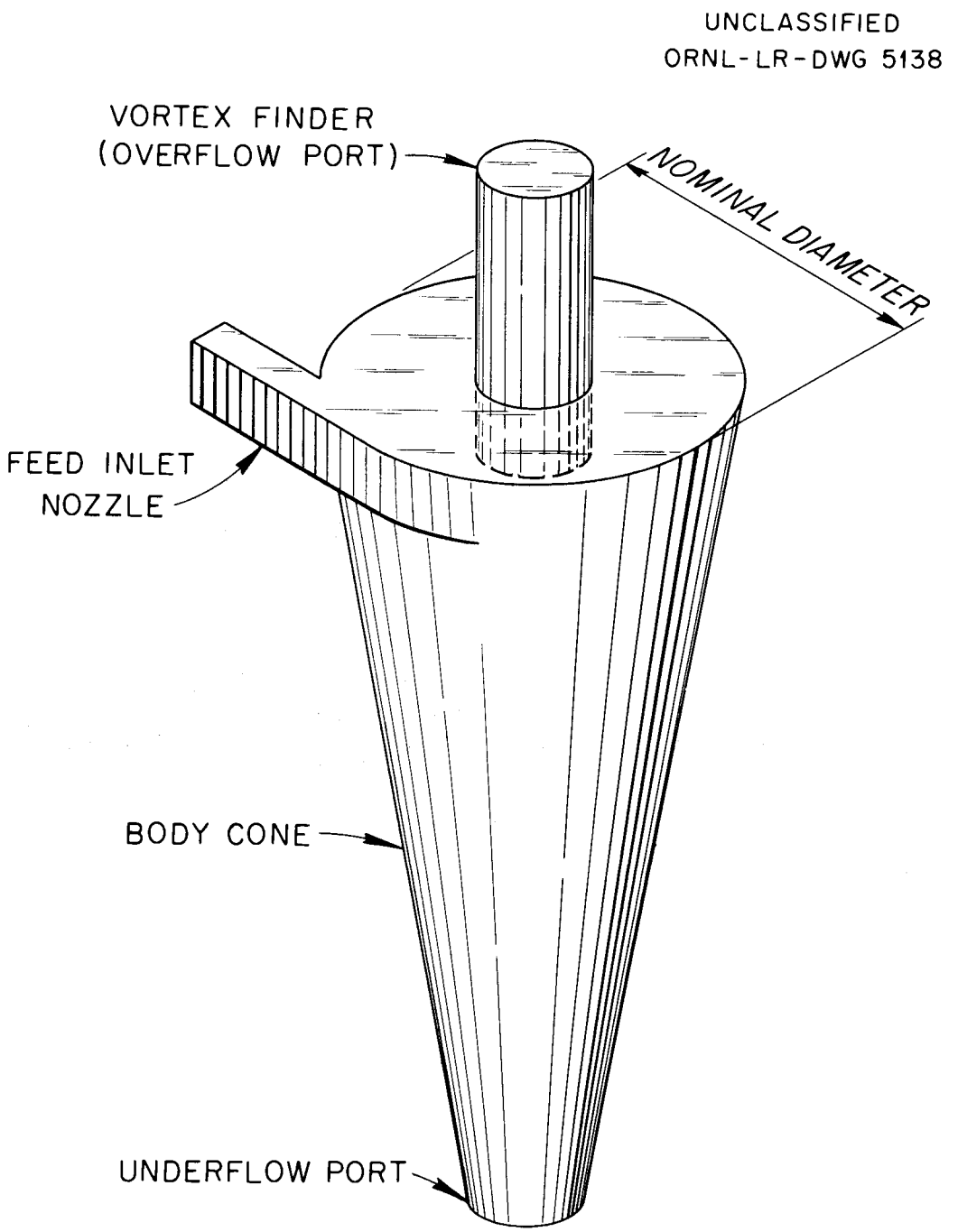


Fig. 1. Typical Hydroclone.

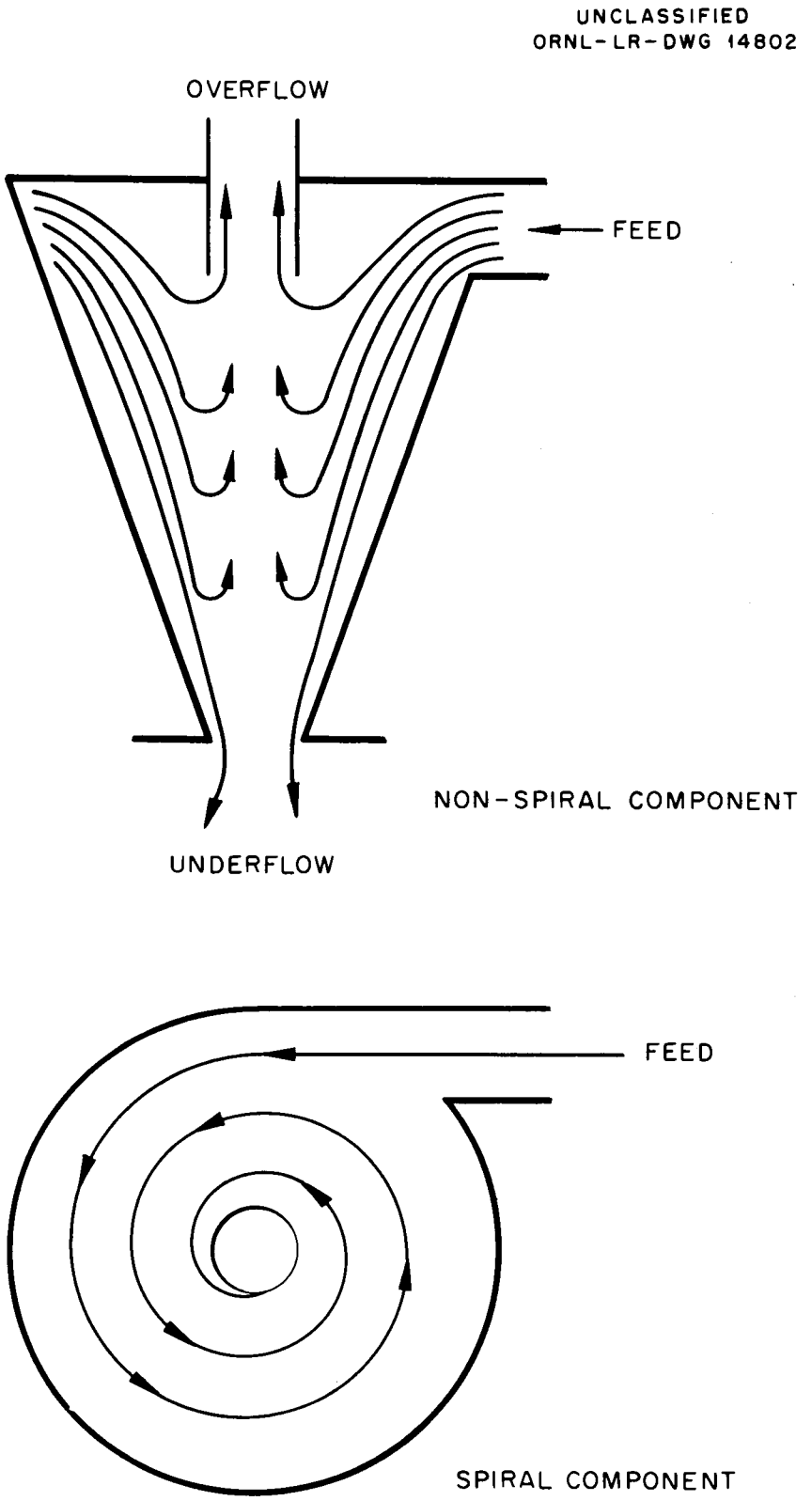


Fig. 2. Hydroclone Flow Patterns.

for comparison since the pressure is a measure of the work done on the liquid. The results reported for pressure drops of 80 ft of liquid would be optimum for any constant pressure drop. The optimum dimensions were expressed as ratios of a primary dimension; i.e., the inside diameter of the hydroclone at the feed port, D_c. The ratios for the 0.25- and 0.40-in. dia hydroclones (Table 1) agree with literature values for larger hydroclones and therefore probably apply to a wider range of sizes.

Table 1. Hydroclone Dimensions

Based on studies on hydroclones of less than 1-in.-dia; values are consistent with literature values for 3- to 6-in.-dia hydroclones

Dimension		Suggested Size (fraction of D_c)	Combination[a] for use with an underflow pot
Symbol	Nomenclature		
D_c	Hydroclone i.d. at feed port	1	1
L	Hydroclone inside length	5-8	6
D_f	Feed port diameter[b]	1/3-1/7	1/4
D_u	Underflow port diameter	1/3-1/6	1/4
D_o	Overflow port diameter, vortex finder i.d.	1/4-1/6	1/5
OD_o	Vortex finder o.d., extension into hydroclone	1/3-1/6	1/4
L_o	Vortex finder length, extension into hydroclone	1/3-1/2	3/8

(a) These dimensions have been used and are suggested for operation with batch underflow accumulation in an induced underflow pot.

(b) Use of a rectangular feed port is usually desirable. The port area may then be made equivalent to circular ports of the diameters suggested.

The hydroclone length, L, showed a distinct maximum efficiency between $L = 5\ D_c$ and $L = 8\ D_c$. The efficiency was less affected by the overflow, underflow, and feed port diameters than by the length, but was a maximum at $D_u = D_o = D_f = 0.20\ D_c$ to $0.25\ D_c$. The length and the underflow port diameter determine an induced underflow ratio (Sec. 4.1) and must be selected to give an acceptable value when operation is of the induced underflow type.

A rectangular feed port with the long axis parallel to the hydroclone axis usually gave better results than a circular port of equal area. Feed port height/width ratios of between 1/1 and 2/1 have been used. The most conventional type of cyclone construction uses a cylindrical section on top of the conical section. The cylinder-cone combinations were no more efficient than a cone of equal length; therefore cylindrical sections were omitted to simplify hydroclone construction.

3.2 Correlation of Efficiency with Hydroclone Size

Constants were calculated for correlations of efficiency with hydroclone size, developed from Stokes' law and from experimental studies reported in the literature.[4,5] The following equation is suggested for rough estimates of the performance of hydroclones with diameters less than 1 in. and with optimum dimension ratios (Sec. 3.1):

$$d_{50} = 5 \times 10^3 \frac{D_c^{0.5} \quad \mu^{0.5}}{(\Delta P)^{0.25} \quad (\rho_s - \rho_l)^{0.5}} \qquad (1)$$

where d_{50} = diameter of particles removed with 50% efficiency, microns

D_c = hydroclone inside diameter at feed port, in.

μ = liquid velocity, lb/ft·sec

ΔP = feed-to-overflow pressure drop, ft of liquid

ρ_s = solid phase density, lb/ft^3

ρ_l = liquid phase density, lb/ft^3

The particle diameter, viscosity, and density terms are fixed by the system to be processed. The hydroclone diameter and the pressure drop can be varied to obtain the necessary hydroclone efficiencies. For small particles, 1 micron dia or less, agglomeration can result in higher efficiencies than would be expected from the true particle size. Some typical results (Table 2) illustrate the effects of pressure drop and the reproducibility of results.

Table 2. Hydroclone Efficiencies

Material: Thorium oxide in water at room temperature; 80 wt % of ThO_2 between 0.6 and 3.0 micron dia.

P_f-P_o: Pressure drop through hydroclone from feed inlet to overflow exit

$B/F = \frac{\text{vol. of underflow}}{\text{vol. of feed}}$

Hydroclone Dimensions		Feed Conditions		Underflow Ratio,	Hydroclone Efficiency,
Diameter, D_c (in.)	Length, L (in.)	P_f-P_o (psi)	Flow Rate (gpm)	100 B/F (%)	E_1 (%)
0.25	1.50	25	0.15	6	27
		49	0.20	6	36
		136	0.30	6	57
		251	0.40	6	67
0.25	1.50	35	0.22	6	42
		35	0.21	6	43
0.40	3.14	35	0.72	6	37,34,40
		35	0.77	6	43
		44	0.87	9	37
0.40	2.40	44	0.76	10	39,44,42

3.3 Correlation of Flow Capacity with Pressure Drop and Size

From theoretical considerations of dimensionally similar hydroclones, the flow is proportional to the square root of the feed-to-overflow pressure difference and to the square of the hydroclone diameter. A more generalized correlation has been developed by Yoshioka and Hotta.[4]

$$\Delta P = \frac{K\,Q^2}{D_c^{0.9}\;D_f^{1.2}\;D_o^{1.9}} \qquad (2)$$

where

ΔP = the feed-to-overflow pressure difference

Q = the volume feed rate

D_c = the hydroclone inside diameter

D_f = the equivalent feed port diameter; i.e., the diameter of a circular port of equal area

D_o = the overflow port inside diameter

K = a constant for given dimensional units

The value of K would actually be determined by the fluid system and the surface finish, and perhaps by other hydroclone dimensions. Some values of K were determined experimentally or from literature data for feed flow in gallons per minute, diameters in inches, and pressure differences in feet of liquid (Table 3). The values of K apply for 80% or more of the feed volume leaving through the overflow port. From Eq. 2, log ΔP versus log Q should give a straight line with a slope of 2.00. The observed slopes for over 30 hydroclones of 0.16, 0.25, and 0.40 in. dia ranged from 2.10 to 2.45, with an average value of 2.27. Similar results have been previously reported[2,3] for larger hydraulic cyclones. Revision of the correlation in Eq. 2 gives much less variation in the value of the new constant, K' (Table 3):

$$\Delta P = \frac{K'\,Q^{2.27}}{D_c^{0.8}\;D_f^{1.3}\;D_o^{2.0}} \qquad (2a)$$

Poor design and construction details such as burrs or nontangent inlet ports result in lower values of K. This would be expected if these faults results in smaller centrifugal fields. When a hydroclone is designed with the dimension ratios suggested as optimum (Table 1), the diameter terms in 2a can be combined into one variable. The equation for hydroclones of less than

1 in. dia then becomes

$$Q = 0.37\ (\Delta P)^{0.44}\ D_c^{1.8} \qquad (3)$$

Table 3. Values of K for Hydroclones

Hydroclone Diameter (in.)	K (ft of liquid) x (in.)^4 x (gpm)^2	K' (ft of liquid) x (in.)$^{4.1}$ x (gpm)$^{2.27}$
0.16	0.060	0.077
0.25	0.062	0.079
0.40	0.07	0.057
3.0 to 6.0[a]	0.15	0.071
3.0[b]	0.15	0.075

(a) Reported by Yoshioka and Hotta.[4]

(b) Calculated from values reported by Kelsall.[2]

4.0 HEAVY-PHASE ACCUMULATION WITH INDUCED-UNDERFLOW OPERATION

4.1 Concept of Induced Underflow Operation

Batch accumulation of the heavy phase in an underflow receiver, a cavity into which the hydroclone underflow port opens (Fig. 3), is a useful alternate method of hydroclone operation. The concentrated heavy phase flows through the underflow port along the hydroclone walls. An equal volume of pot solution returns through the center region of the underflow port. This type of operation resembles that of dust collection in a gas-solid cyclone separator. Settling out in the underflow pot could increase the effectiveness of a hydroclone operated in this way, but would take place only if particles were not too small and thermal convection from radiation heating did not interfere.

UNCLASSIFIED
ORNL-LR-DWG 14803

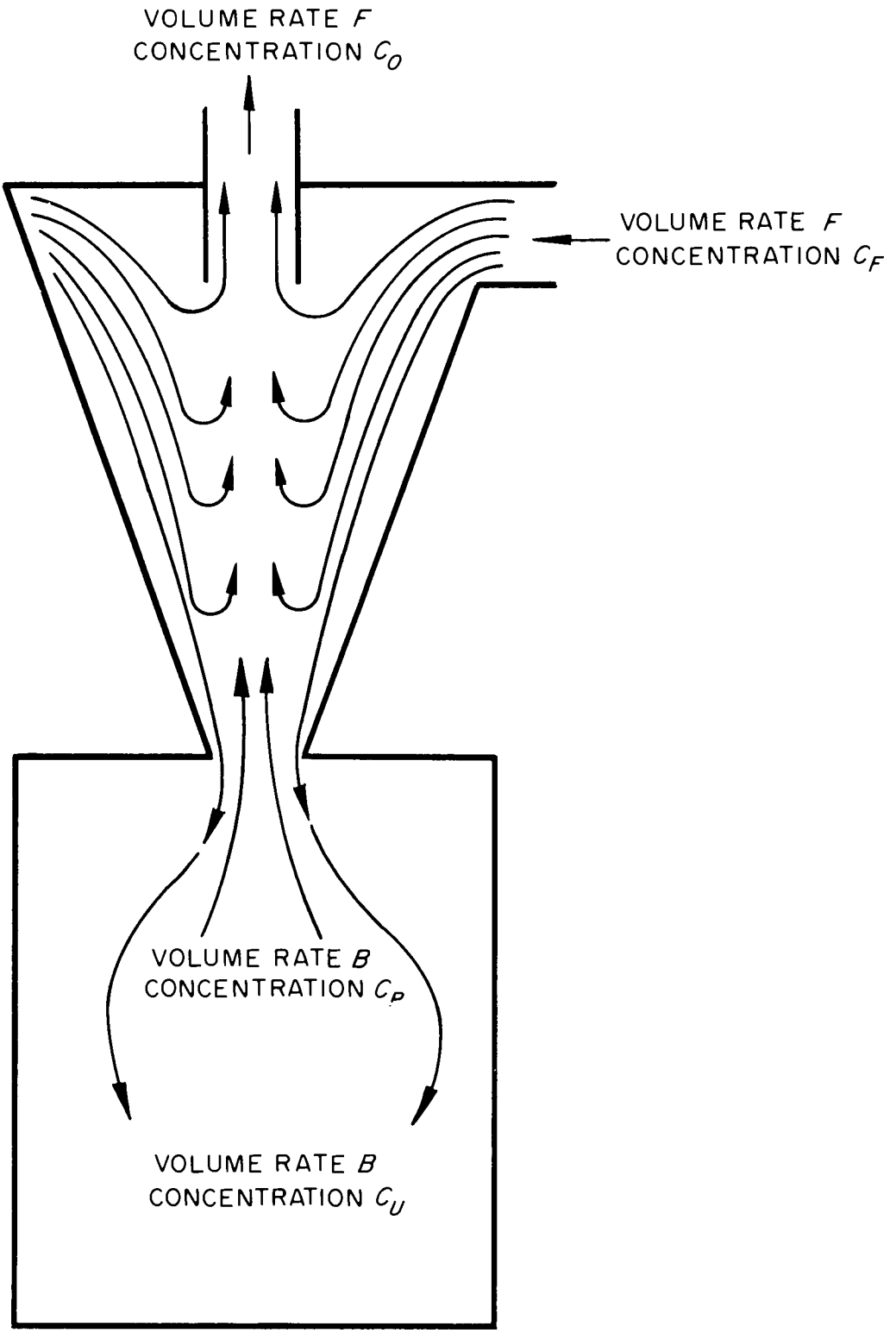


Fig. 3. A Hydroclone and Underflow Pot.

This method of operation eliminates an otherwise difficult flow control problem. With a continuous underflow, obtaining high concentration factors requires a small volume underflow rate. Metering this slurry stream would be difficult, especially if the slurry was to be let down from 100 to 1 atm pressure, as would be the case in several proposed aqueous-system homogeneous reactors. The batch underflow accumulation permits isolation of the hydroclone and pot with batch letdown of the complete hydroclone and pot volume without disturbance of reactor operation.

The mathematical analysis of induced underflow pot operation requires several new symbols in addition to those previously defined. Also, several previously defined quantities take on additional meanings (Fig. 4):

F = the volume feed flow rate is also the volume overflow rate

B = the volume rate of feed liquid flow into the underflow receiver, is also the volume rate of flow from the underflow pot into the overflow.

B_r = recycle rate from the underflow receiver into the hydroclone and back into the underflow receiver, a flow not included in the values of B.

E_1 = the usual hydroclone efficiency, which may be termed a "feed-to-pot" efficiency

S = amount of material (solids) in underflow receiver

C_p = concentration of the stream returning from the underflow receiver to the hydroclone

E_2 = efficiency for returning to the underflow receiver the solids in the flow from the receiver to the overflow stream; a material balance to be made (Eq..4) will result in a mathematical definition of E_2 which may be called a "pot-to-pot" efficiency

θ = time with the time unit used for the flow rates

CF = a concentration factor defined by C_p/C_f

4.2 Determination of Induced Underflow Ratio and Concentration Factors

Relations for the performance of a hydroclone and induced underflow pot can be obtained from algebraic rearrangements of simple material balances.

UNCLASSIFIED
ORNL-LR-DWG. 25135

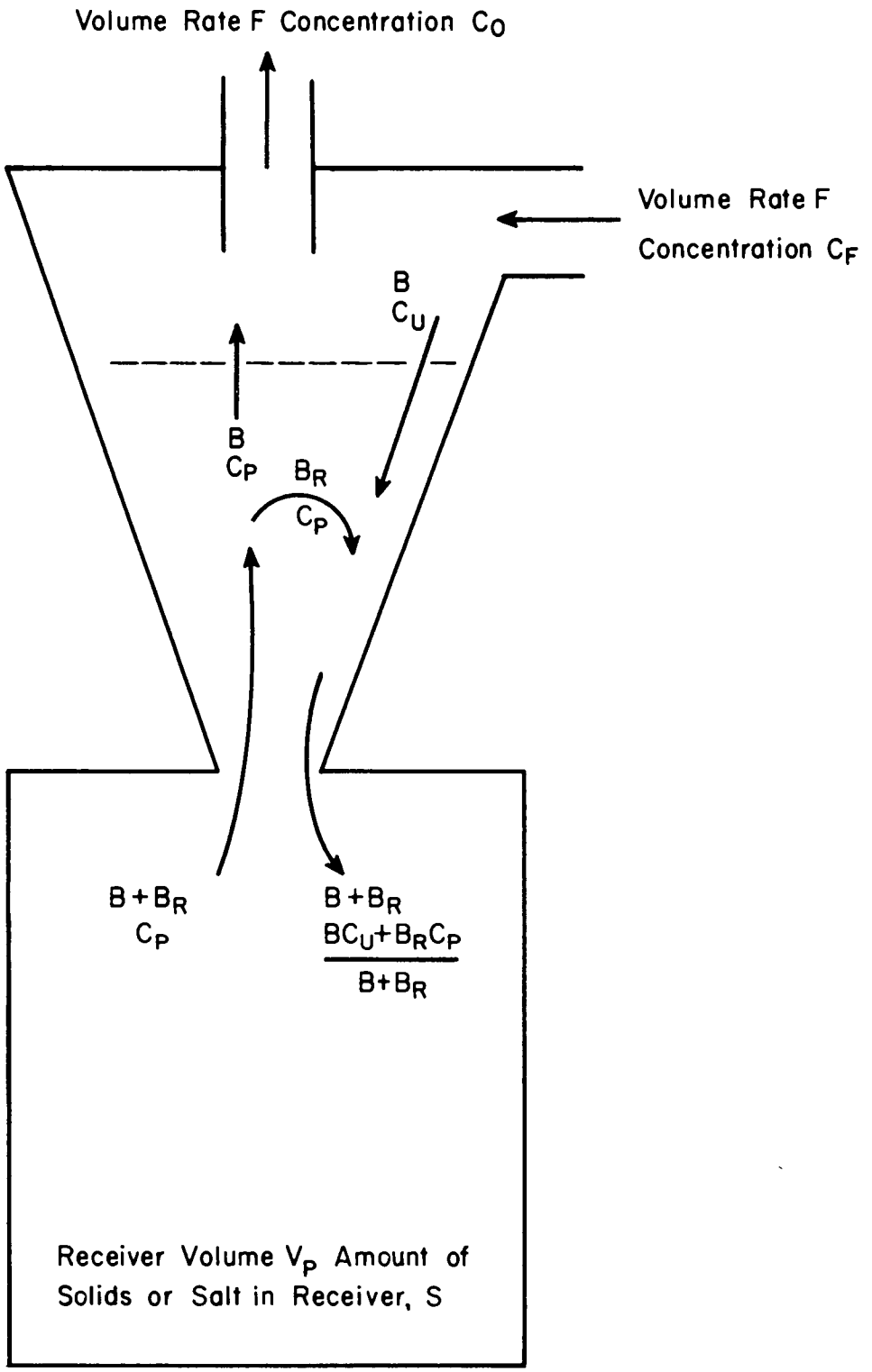


Fig. 4. Induced Underflow Receiver Nomeclature.

For the hydroclone, the underflow receiver, and for the whole unit these are:

$$FC_f d\theta + (B + B_r)\, C_p\, d\theta = (B + B_r)\left(\frac{BC_b + B_r C_p}{B + B_r}\right) d\theta + FC_o d\theta \qquad (4)$$

$$dS = (B + B_r)\left(\frac{BC_b + B_r C_p}{B + B_r}\right) d\theta - (B + B_r)\, C_p d\theta \qquad (5)$$

$$dS = FC_f d\theta - FC_o d\theta = (C_f - C_o)\, F d\theta \qquad (6)$$

The definition of E_1 and E_2 result in the following material balances for the solids in the overflow and the underflow streams:

$$FC_o d\theta = FC_f\,(1 - E_1)\, d\theta + BC_p\,(1 - E_2)\, d\theta \qquad (7)$$

$$(B + B_r)\left(\frac{BC_b + B_r C_p}{B + B_r}\right) d\theta = B_r C_p\, d\theta + FC_f E_1 d\theta + BC_p E_2 d\theta \qquad (8)$$

Only three of the above five equations are independent since Eq. 6 can be derived from Eqs. 4 and 5, and Eq. 8 can be derived from Eqs. 4 and 7. Equation 7 is a mathematical definition of E_2; i.e., E_2 is defined to make Eq. 7 true. For equilibrium conditions (infinite time), C_f equals C_o, C_b equals C_p, and dS equals 0. Substituting $C_f = C_o$ in Eq. 7 and solving for an equilibrium concentration factor, $(CF)_\infty$, gives

$$(CF)_\infty = \frac{C_{p_\infty}}{C_{f_\infty}} = \frac{F}{B} = \left(\frac{E_1}{1 - E_2}\right) \qquad (9)$$

Two methods of determining B/F, the induced underflow ratio, were developed since this ratio, values of E_2, and the already known values of E_1 are needed to calculate $(CF)_\infty$. Both methods use pure water feed to the hydroclone and a soluble salt in the underflow pot. The material balance equations apply to this situation also, with the concentrations referring to salt concentrations instead of suspended solids concentrations; then $C_f = 0$, C_{p_o} is the initial underflow receiver concentration, $E_2 = 0$, and $C_b = 0$.

For operation with a soluble salt in the underflow receiver, either Eq. 4 or Eq. 7 can be reduced to the form $BC_p = FC_o$, from which

$$B/F = C_o/C_p = C_{o_o}/C_{p_o} \tag{10}$$

The pot concentration, C_p, is the concentration at the underflow port and is not easily measured. The initial underflow receiver concentration can be determined from samples of the solution used to fill the pot. Values of C_o for plotting against θ can be obtained from overflow stream samples over a period of time. Values of C_{o_o} obtained by extrapolating this curve to zero time can be substituted in Eq. 10 with values of C_{p_o} to give a value of B/F.

The second method of determining B/F requires thorough mixing of the underflow receiver contents so that the value of C_p is also the average concentration of the receiver contents. This leads to the relation $S = V_p C_p$, from which

$$dS = V_p dC_p = V_p \frac{dC_o}{B/F} \tag{11}$$

Equation 11, which is derived from Eq. 10, can be combined with Eq. 6 and the differential expression integrated with the limits θ_1 to θ_2 and C_{o_1} to C_{o_2} to give

$$V_p \frac{dC_o}{B/F} = (C_f - C_o)\, F d\theta = -C_o F d\theta$$

$$\int_{\theta_1}^{\theta_2} d\theta = \frac{-V_p\, F}{F\ \ B} \int_{C_{o_1}}^{C_{o_2}} \frac{d\, C_o}{C_o}$$

$$B/F = \frac{V_p}{(\theta_2 - \theta_1)\, F} \ln \frac{C_{o_1}}{C_{o_2}} \tag{12}$$

The use of Eq. 12 requires only overflow samples vs. time and values for the feed flow rate and the underflow receiver volume.

4.3 Performance of Induced Underflow Receivers

Observed B/F Values. Values of the induced ratio were determined from both Eqs. 10 and 12. The soluble salt selected was lithium chloride since the ORNL analytical laboratories were equipped for rapid analysis of lithium in water. An alkali or base could be used if concentrations were kept low enough to minimize density effects.

The B/F ratio decreases as the hydroclone length is increased. A small-diameter channel connecting the hydroclone and the underflow receiver has the same effect as an increase in hydroclone length, and the observed B/F ratios may be correlated fairly consistently with the hydroclone diameters divided by the sum (Fig. 5) of the hydroclone and connecting channel lengths. Since some of the scattered points are apparently due to underflow port diameter variations, this diameter would be expected to affect the B/F values.

When Eq. 10 was to be used, the induced underflow pot was completely filled to slightly above the underflow port into the hydroclone with solution of a known lithium chloride concentration. The feed flow rate is adjusted to the selected value as rapidly and smoothly as possible with the initial flow at zero time. Samples of the overflow stream are taken at 10, 20, 30, 40, 60, and 120 sec, and sometimes at 3, 4, 5, and 10 min. The sample concentrations are plotted as log C_o vs. time on a linear scale since this tends to give a straight line (Fig. 6). The zero time value, C_o, obtained by extrapolation and the C_{p_o} from the known initial underflow receiver concentration are substituted in Eq. 10.

When Eq. 12 was to be used, mechanical agitation by a magnetic stirrer (in a plastic or glass underflow receiver) was applied, or thermal convection agitation was assumed suitable. The underflow port was on the sidewalls of the cylindrical pots to minimize vortex effects. For complete mixing, log C_o vs. time is a straight line with a constant slope for concentration of 100 ppm or more (Fig. 7). Any upward curvature as low concentrations are reached is evidence of incomplete mixing. Although the hydroclone flow pattern extends down into the underflow receiver, it does not cause complete mixing even in very small pots.

Values of B/F from Eq. 12 were higher than those from Eq. 10 for comparable conditions (Fig. 5). This difference would be expected from probable sources of error. If mixing is incomplete, C_p is less than instead of equal to S/V_p and the values calculated for B/F will be too large. The effects of initial flow irregularities on the use of Eq. 10 are not easily determined. The most probable effects are low values of B/F since the extrapolation to zero time may have to be made from points that give low values of the slope.

UNCLASSIFIED
ORNL-LR-DWG. 25136

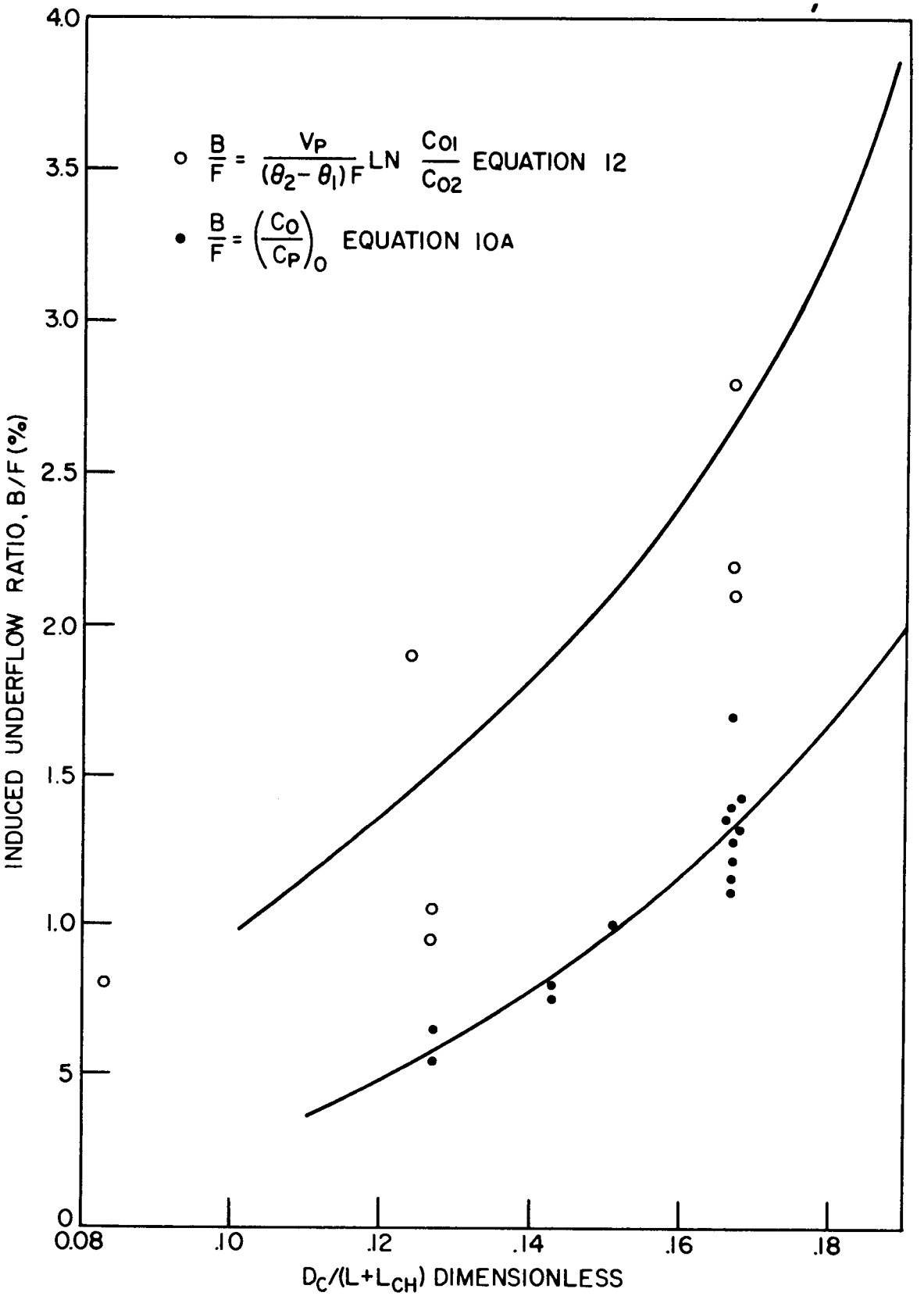


Fig. 5. Correlation of Induced Underflow Ratio.

UNCLASSIFIED
ORNL-LR-DWG. 25137

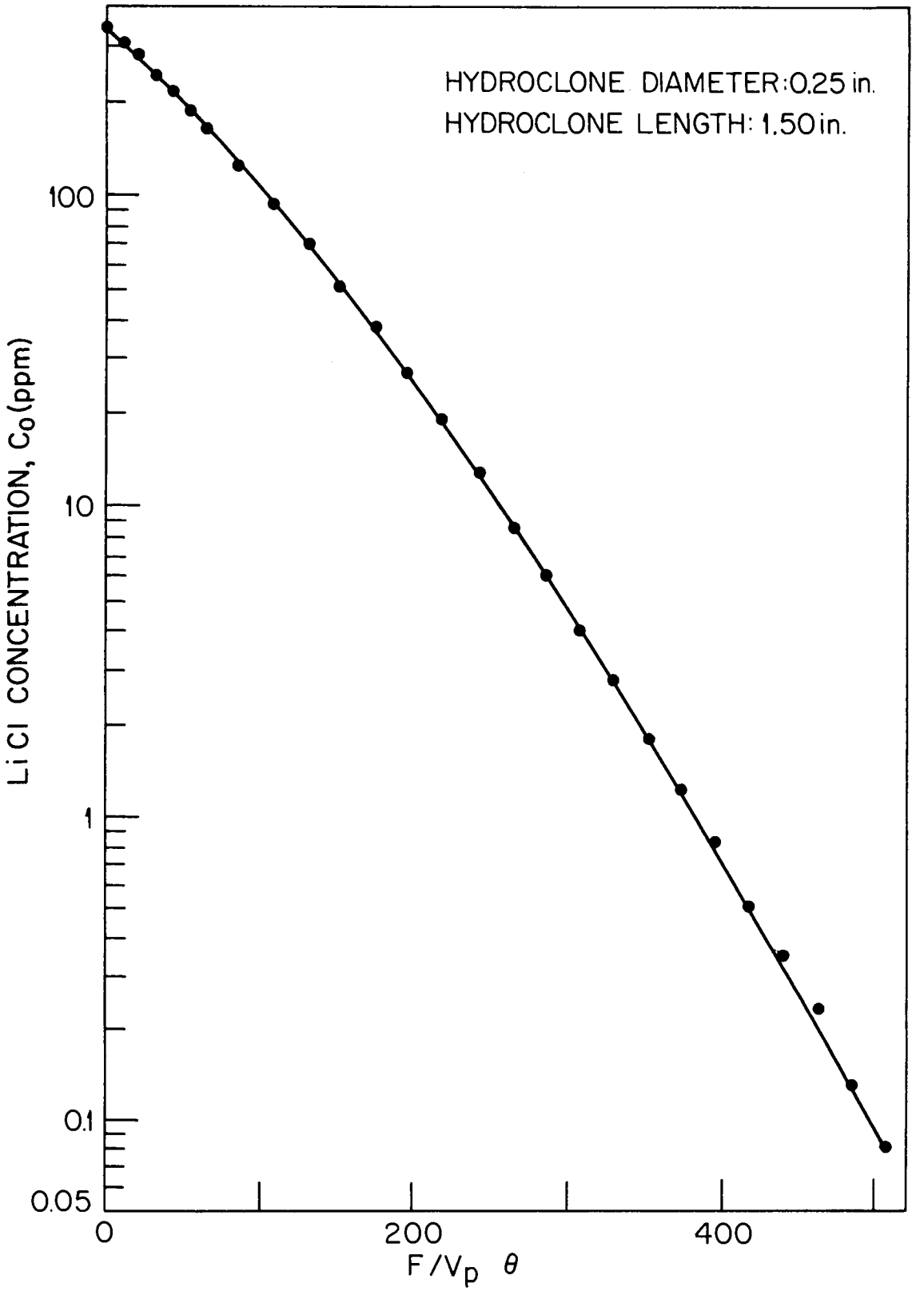


Fig. 6. Determination of an Underflow Ratio from the Overflow Stream Concentration versus Time.

UNCLASSIFIED
ORNL-LR-DWG. 25138

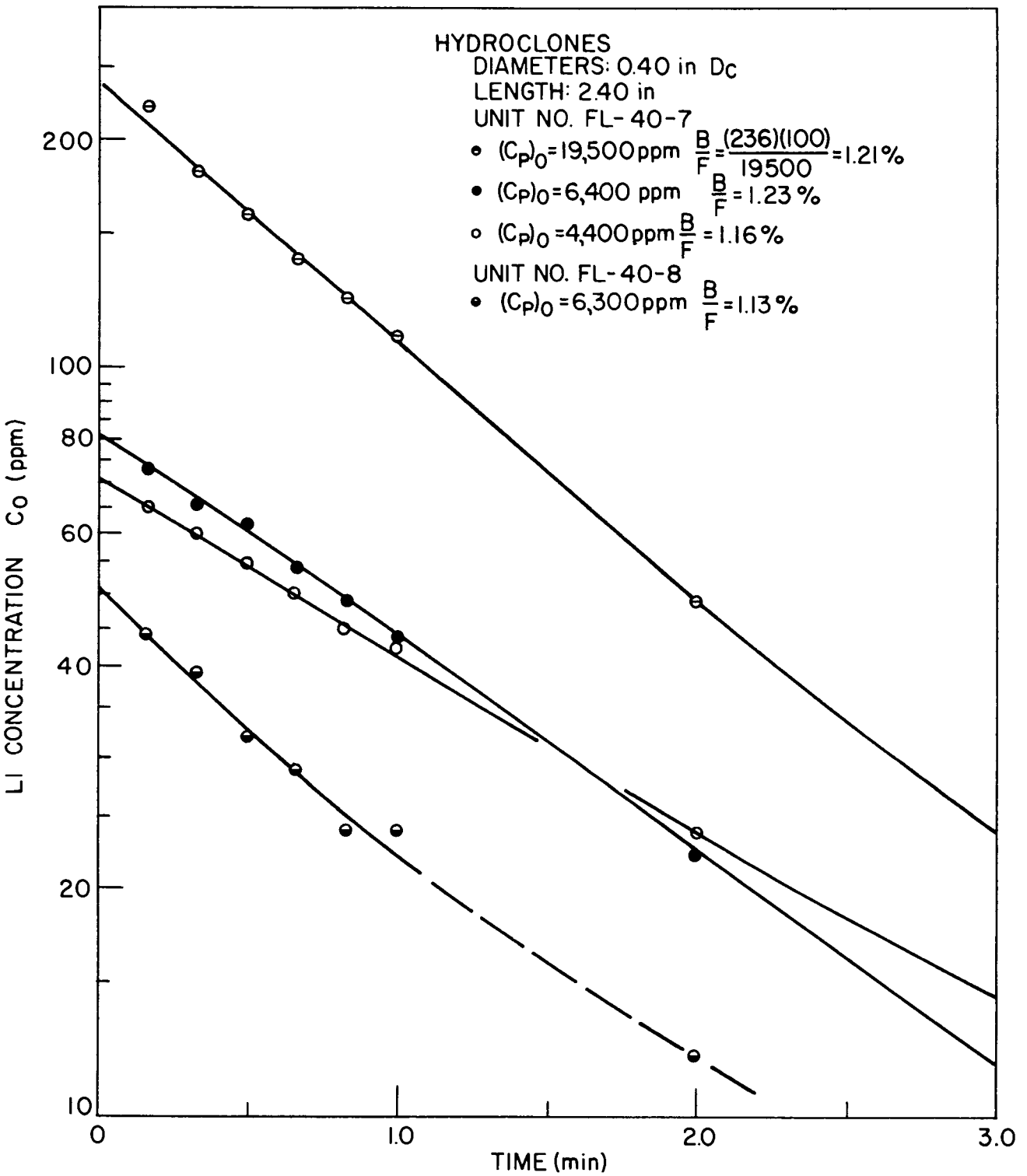


Fig. 7. Induced Underflow Rate Determination

Determination of E_2. Values of E_2, a pot-to-pot efficiency, are difficult to obtain because of the elusive nature of the induced underflow stream. One method involves a pure water feed to a hydroclone with a slurry in the underflow receiver stirred to maintain a uniform concentration. Then Eq. 7 can be simplified to give an equation for E_2:

$$E_2 = 1 - FC_o/BC_p \qquad (13)$$

Either the overflow stream and the underflow receiver can both be sampled, or the values of C_o can be extrapolated to C_{o_o} where C_{p_o} is known. Combining Eqs. 6 and 7 for $C_f = 0$ and $S = V_pC_p$ gives:

$$dS = - C_oFd\theta = V_pdC_p = V_p \frac{FdC_o}{B\,(1-E_2)} \qquad (14)$$

which can be integrated from θ_1 to θ_2 and C_{o_1} to C_{o_2} to give:

$$E_2 = 1 - \frac{V_p}{B\,(\theta_2 - \theta_1)} (\ln C_{o_1}/C_{o_2}) \qquad (15)$$

Therefore E_2 can be obtained from the slope of $\ln C_o$ vs. time where V_p and B are known:

The values of E_2 would be expected to be higher than the values of E_1 for similar conditions, and this has been observed experimentally (Table 4). When E_1 and E_2 are expressed as weight fractions, the limited experimental data fit the equation when the constant n has a value of about 2.0:

$$E_2 = n\,E_1 - (n - 1)\,E_1^{\,2} \qquad (16)$$

Observed Concentration Factors. Values of $(CF)_\infty = (C_p/C_f)_\infty$ can be calculated from Eq. 9 after values of E_1, E_2, and B/F are known. Values of S/V_pC_f should equal this concentration factor if the underflow receiver is stirred to maintain uniform concentrations. Values for S/V_pC_f of 35 to 4500 for stirred underflow receivers (Table 4) and receivers without mechanical agitation (Table 5) have been observed.

Table 4. Hydroclone Performance in the Induced Underflow Pot System

Hydroclone dimensions

Nominal diameter	0.25 in.
Feed inlet	0.063 x 0.033 in.
Vortex finder	0.53 in. i.d.
Underflow port	0.075 in. i.d.
Cone length	1.5 in.

Operating conditions

Feed pressure	35 psi
Feed flow	0.20 gpm
Underflow ratio	1.98%
Agitation by a magnetic stirrer	

Solid ThO_2[a] Size (microns)	E_1 (%)	E_2 (%) Eq. 12	E_2 (%) Eq. 10	S/V_pC_f, Exptl.	C_p/C_f, Calc.[b]
1	26	52	49	35.6	26 lowest
1	29	--	--	37.5	31 highest
2	35	46	66	78	33 lowest
2	50	--	--	93	74 highest
4	95.8	90.1	94.0	2300	490 lowest
4	96.8	95.7	94.3	2420	1132 highest

(a) Approximate d_{50}.

(b) $$\frac{C_p}{C_f} = \frac{F}{B} \frac{E_1}{1 - E_2}.$$

Table 5. Experimental Concentration Factors for Underflow Pot Operation

No mechanical agitation of underflow receiver

Hydroclone Diameter (in.)	Material	Material Size			Observed Concentration Factor, S/V_pC_f
		50% ≤d ≤50% (microns)	Wt % Within		
			(wt %)	Range (microns)	
0.25	ThO_2	4.1	70	3.0 to 7.1	2300
		4.1	70	3.0 to 7.1	2420
		1.8	71	0.8 to 4.2	78
		1.8	71	0.8 to 4.2	93
	ZrO_2	1.0	80	0 to 4.0	4500
0.40	Fe_2O_3[a]	0.5	80	0.2 to 0.5	270[b]

[a] Observed concentration factor and particle size measurements were for different samples of Fe_2O_3.

[b] Based on the total iron in the hydroclone feed and would be higher if based on insoluble iron only.

5.0 DESIGN FEATURES FOR HOMOGENEOUS REACTOR CHEMICAL PROCESSING

Aqueous homogeneous reactor systems put severe requirements on hydroclone designs in addition to the liquid-solid separation required. The 300°C temperature, the 2000 psi pressure, and the chemical activity of uranyl sulfate solution at this temperature and pressure limit the materials of construction. The radiation level of the process can damage materials of construction, and it makes necessary a minimum amount of maintenance which must be done remotely. The capacity and efficiency of a processing system must meet the nuclear reactor requirements, which are usually set in terms of permissible poison levels.

5.1 Corrosion and Materials of Construction

Materials and methods of fabrication which given good dimensional control and surface finishes of better than 20 microinches can be used to produce hydroclones. Corrosion and erosion will be of the order of those expected for 20 ft/sec velocities for the fluid system handled. Therefore general corrosion studies can be used to select materials of construction for hydroclones.

Acceptable materials of construction for hydroclones to be used at 250°C would be type 316 stainless steel for water and titanium for uranyl sulfate solutions. Titanium hydroclones have been corroded at rates of less than 10 mpy by uranyl sulfate solutions containing 10-400 g of uranium per kilogram of H_2O at 250-300°C (Figs. 8 and 9). It is believed that titanium hydroclones will withstand uranyl sulfate of any concentrations now propose for aqueous homogeneous reactors. Stainless steel hydroclones tested with uranyl sulfate solutions containing 10-15 g of uranium per kilogram of H_2O at 250-320°C have shown corrosion rates from less than 10 mpy to over 100 mpy. The variations are probably due to minor variations in conditions since for uranyl sulfate on stainless steels there are critical velocities which separate regions of high and low corrosion. Velocities at the hydroclone port or wall are of the order of 20 ft/sec. Stainless steel hydroclones are considered undependable for uranyl sulfate solutions, although they are probably adequate for coolant water streams. Annealed gold has been found to be a very useful gasket material. Corrosion studies for most commercially available metals and for other materials in aqueous UO_2SO_4 solutions have been reported by the Reactor Experimental Engineering Division (Oak Ridge National Laboratory) in Homogeneous Reactor Project Quarterly Reports and in other reports.

5.2 Remote Maintenance Requirements

The Homogeneous Reactor Test hydroclone had to be designed, as did the remainder of the system, for either no maintenance or remote maintenance under water. The need for a different capacity, underflow ratio, or efficiency, or the need for replacing a corroded or plugged hydroclone would require inter-

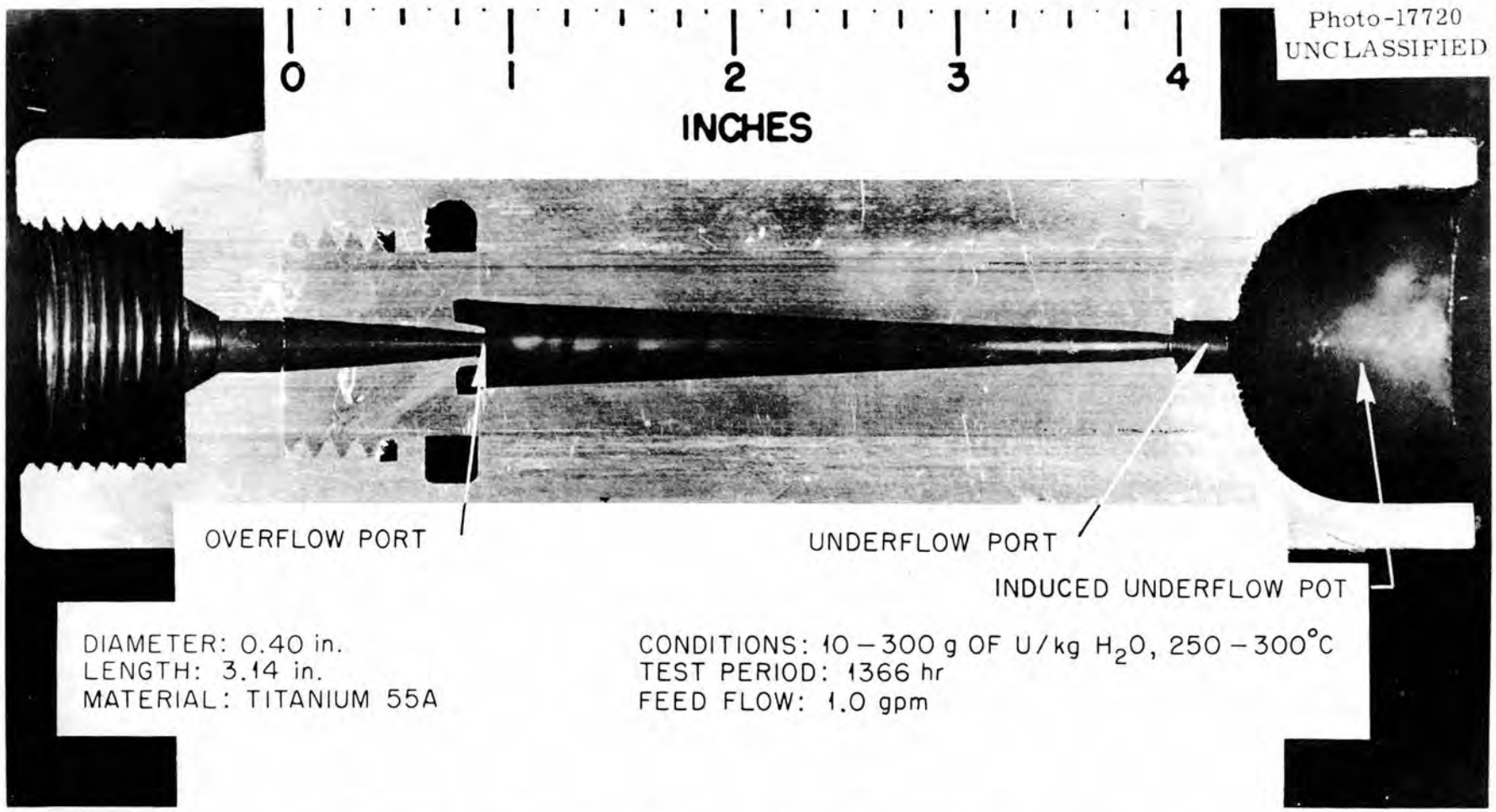
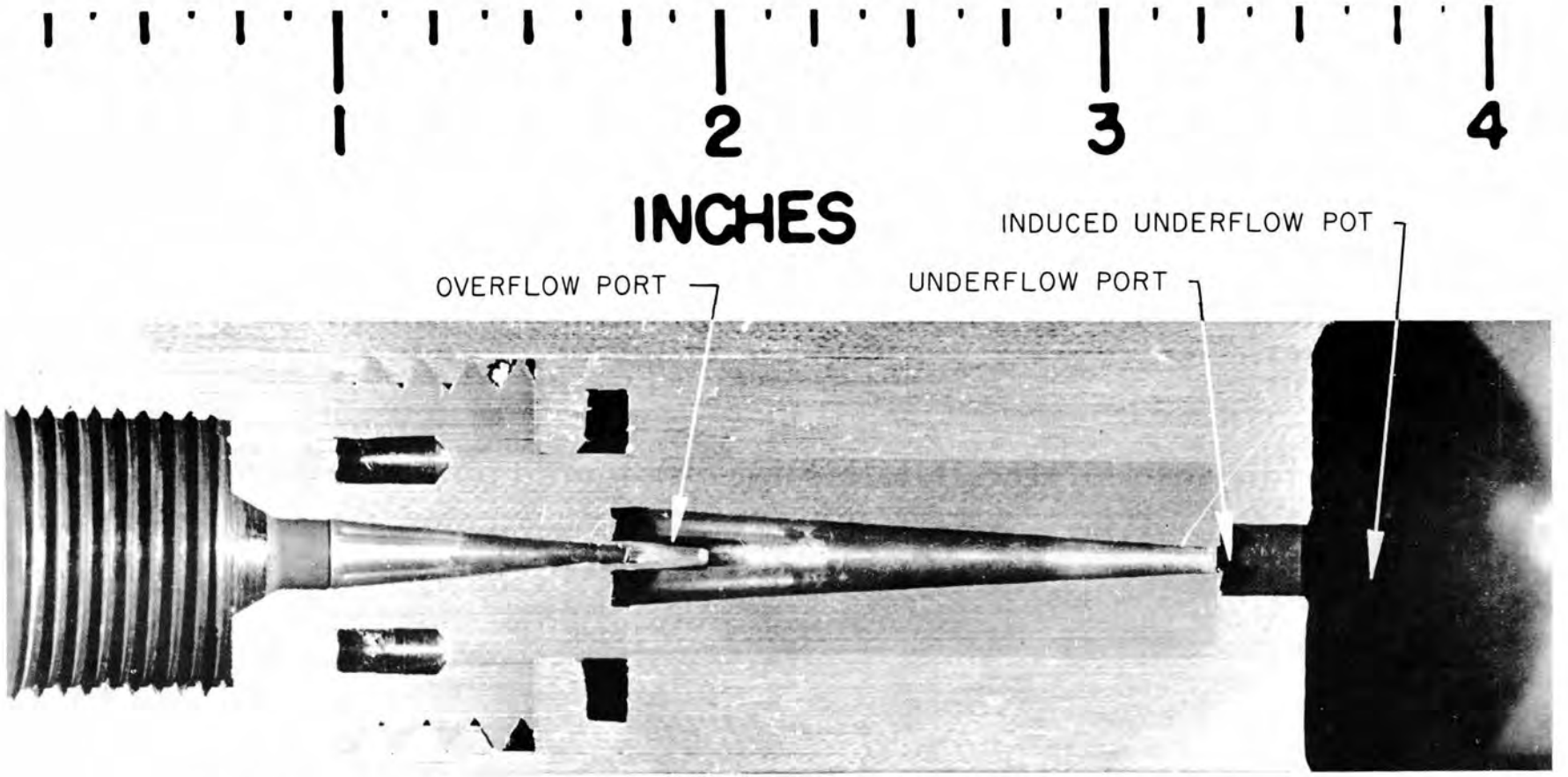


Fig. 8. Corrosion of a 0.40-in.-dia Titanium-Lined Hydroclone.



DIAMETER: 0.25 in.
LENGTH: 1.50 in.
MATERIAL: TITANIUM 55A

CONDITIONS: 10 g OF U/kg OF H_2O, 300°C
TEST PERIOD: 3975 hr
FEED FLOW: 0.23 gpm

Fig. 9. Corrosion of a 0.25-in.-dia Titanium-Lined Hydroclone.

Photo-17719
UNCLASSIFIED

changeable hydroclone units. Therefore a design was developed to permit replacement of a hydroclone in a radioactive system by use of a flanged closure and remote tools (Fig. 10). All connections are in the lower flange, including the underflow pot on which the flange is mounted. The flange bolts, the hydroclone retainer, and the hydroclone could be removed and replaced by remote tools. This design was not completely satisfactory in that the retainer was difficult to remove after high-temperature operation. This retainer has been redesigned to screw into a cam-held insert and to bear on a stationary element instead of revolving on the hydroclone top.

5.3 Operating Flexibility

In commercial applications hydroclones have been set in parallel to increase capacities and in series to increase the concentration factors. Such usage would also be possible with reactor systems. In batch-accumulation operation, parallel units might be able to use one common underflow pot. This type of operation is being tested to determine if corrosion or solids accumulation can result in zero underflow and thus zero efficiency for one of the parallel units.

No plugging of feed or overflow ports was observed during application of hydroclones to a variety of precipitated corrosion and fission products in high-temperature high-pressure systems. The port sizes were 0.05-0.10 in. dia. The possibility of plugging could be minimized by use of a coarse screen or scalping hydroclones to catch particles larger than the hydroclone port diameter. The underflow ports did not become plugged in induced underflow operation. When the underflow was temporarily interrupted in hydroclones designed for continuous underflow takeoff, the plugs of solids which accumulated in the underflow line or port were difficult to remove and hydroclone erosion (Fig. 11) resulted.

6.0 PREDICTED PERFORMANCE OF HRT HYDROCLONES

Relative performance curves are presented as calculated for HRT Chemical Plant conditions for the three sizes of hydroclones, 0.25, 0.40, and 0.56 in. (Figs. 12-17). Not all the dimension of these units (Table 6) agree with the dimension ratios previously suggested as optimum (Table 2).

These curves are based on the ORNL development studies and the literature correlations for hydraulic cyclones.[3,5] The physical properties used for the solution and solids were those expected for the HRT core solution at 300°C with $\mu = 0.7 \times 10^{-4}$ lb/ft·sec and $\rho_s - \rho_l = 110$ lb/cu ft. A reduced fractional recovery curve of E_1 vs. d/d_{50} as presented by Yoshioka and Hotta[5] was used with Eq. 1 to calculate the efficiencies. The other quantities were calculated from the correlations which have been presented.

UNCLASSIFIED
ORNL-LR-DWG 14055

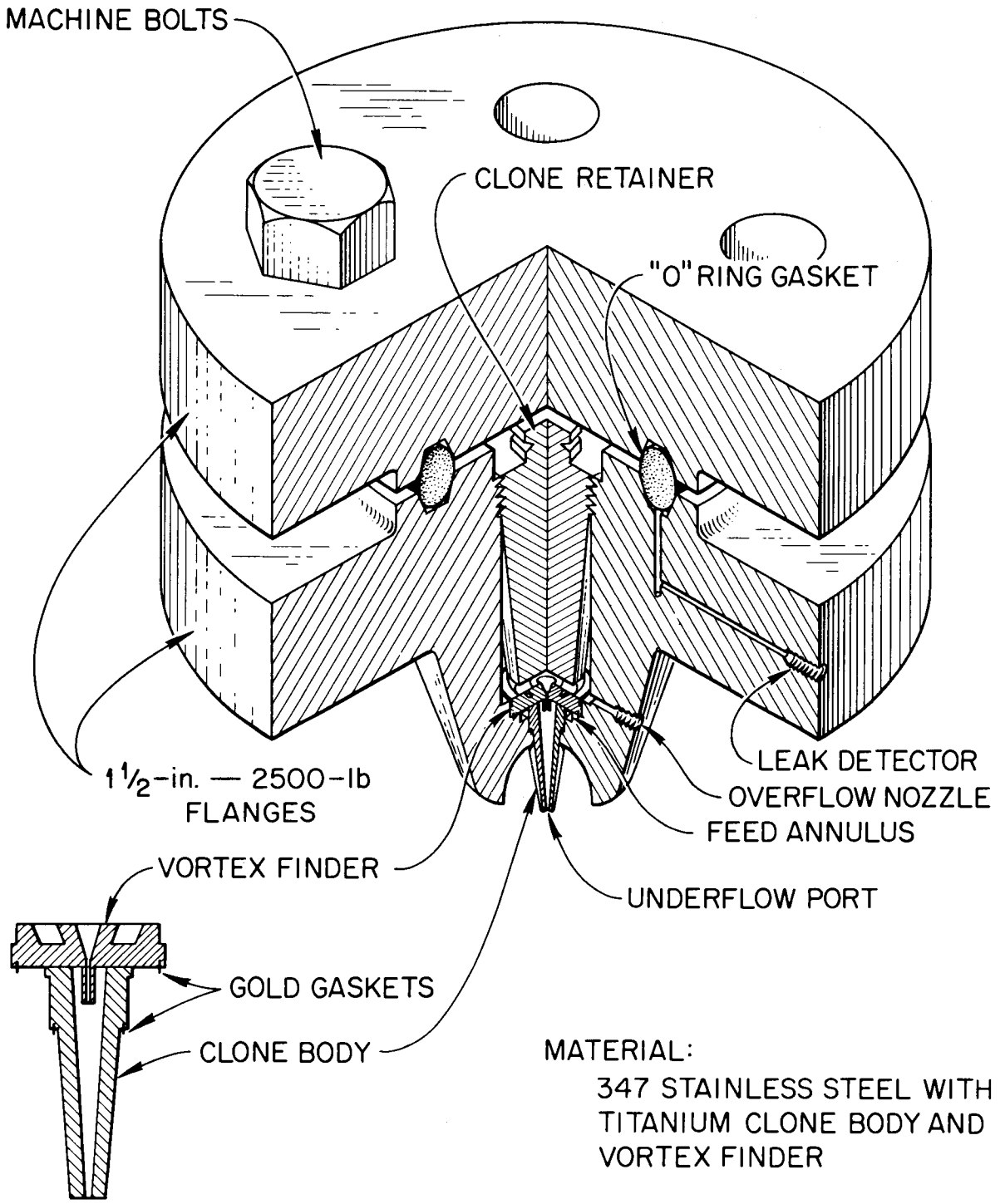
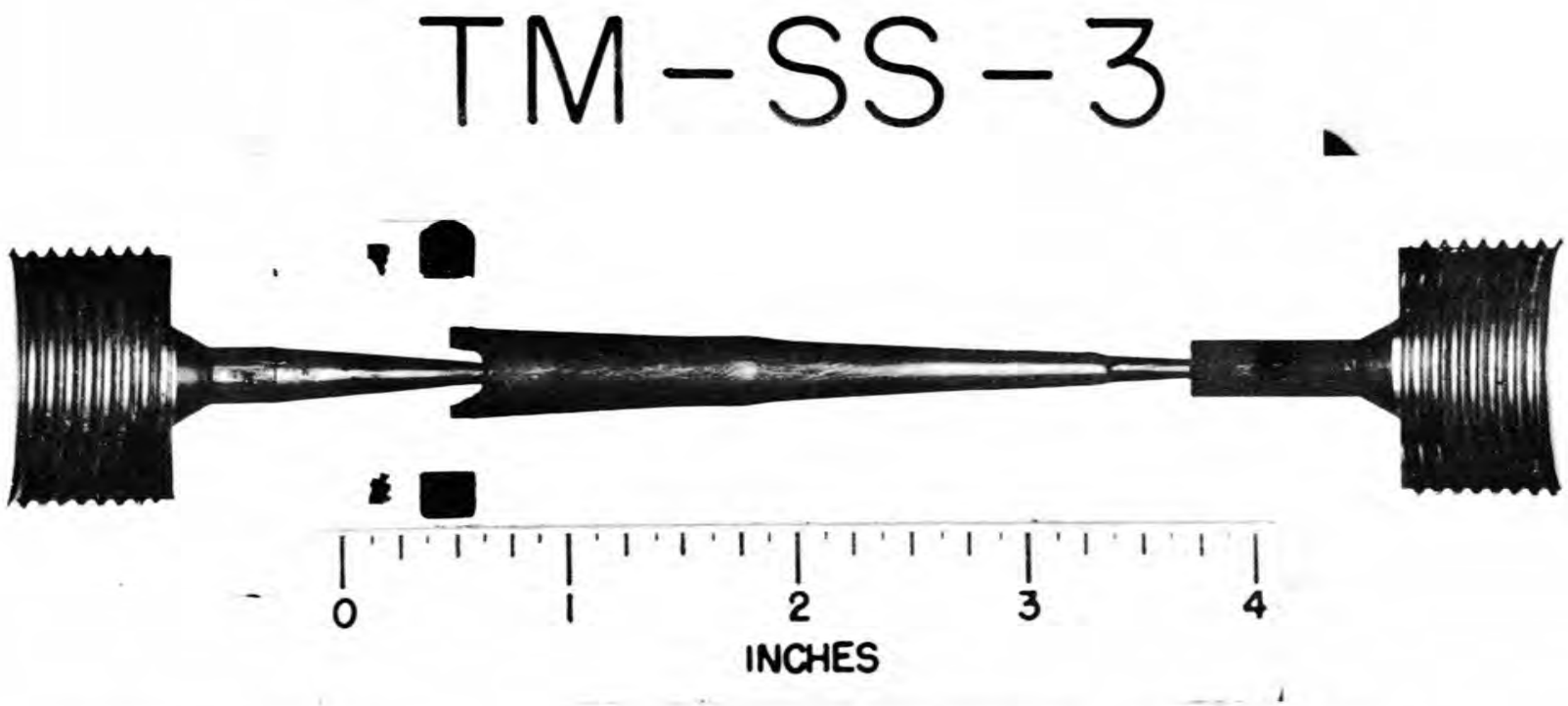


Fig. 10. Cross Section of Integrally Flanged Hydroclone.



DIAMETER: 0.40 in.
LENGTH: 3.14 in.
MATERIAL: 347 STAINLESS STEEL

CONDITIONS: 15 g OF U/kg OF H_2O, 250°C
TEST PERIOD: 200 hr
FEED FLOW: 0.6 gpm
REMARKS: ¾-in. DEPTH PLUG OF SOLIDS ABOVE UNDERFLOW PORT

Photo-18122
UNCLASSIFIED

Fig. 11. Corrosion-Erosion of a 0.40-in.-dia 347 Stainless Steel Hydroclone.

UNCLASSIFIED
ORNL-LR-DWG. 25139

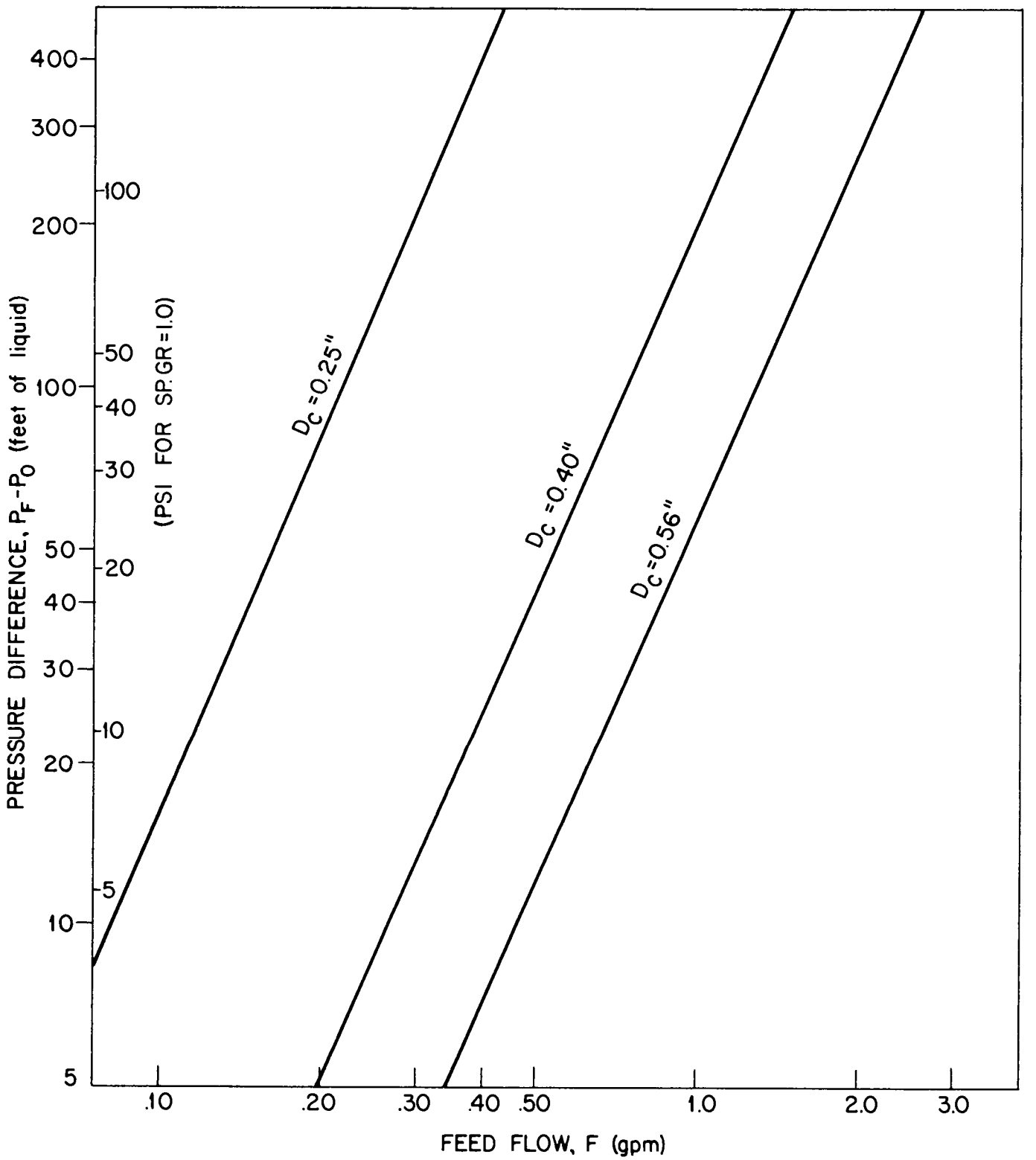


Fig. 12. Hydroclone Pressure Drop vs Flow Rate.

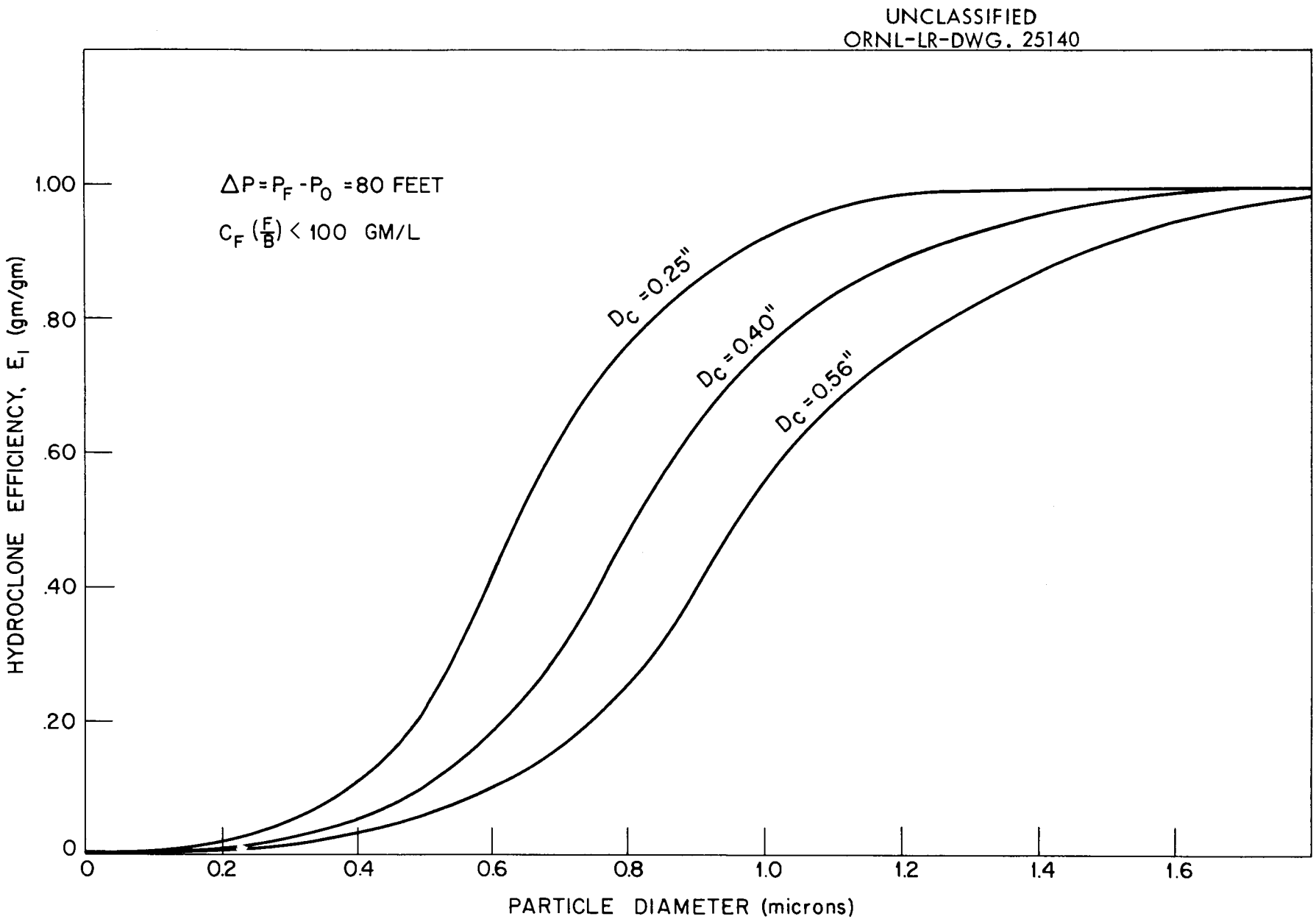


Fig. 13. Hydroclone Efficiency vs Particle Diameter.

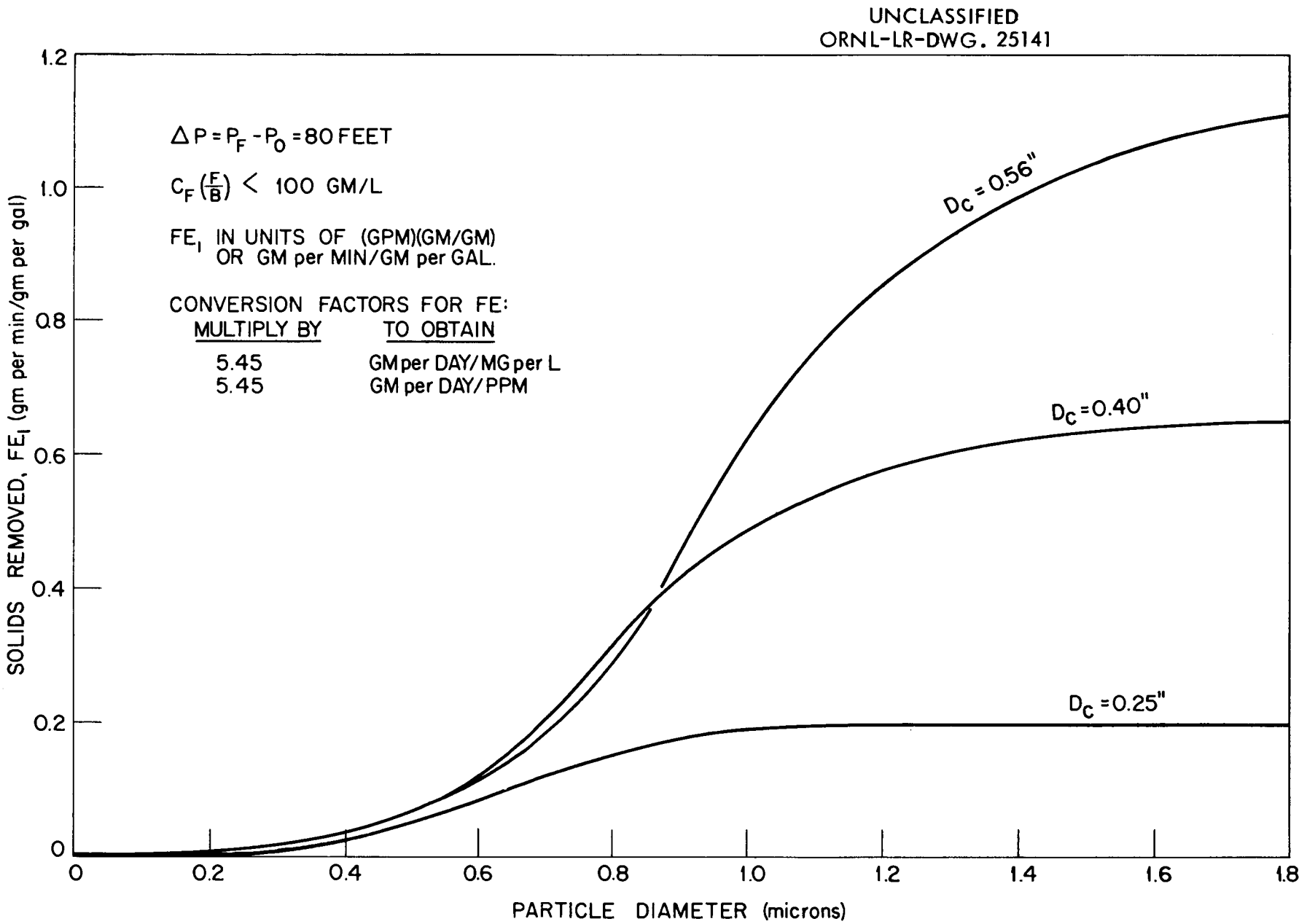


Fig. 14. Rate of Solids Removal by Hydroclone vs Particle Diameter.

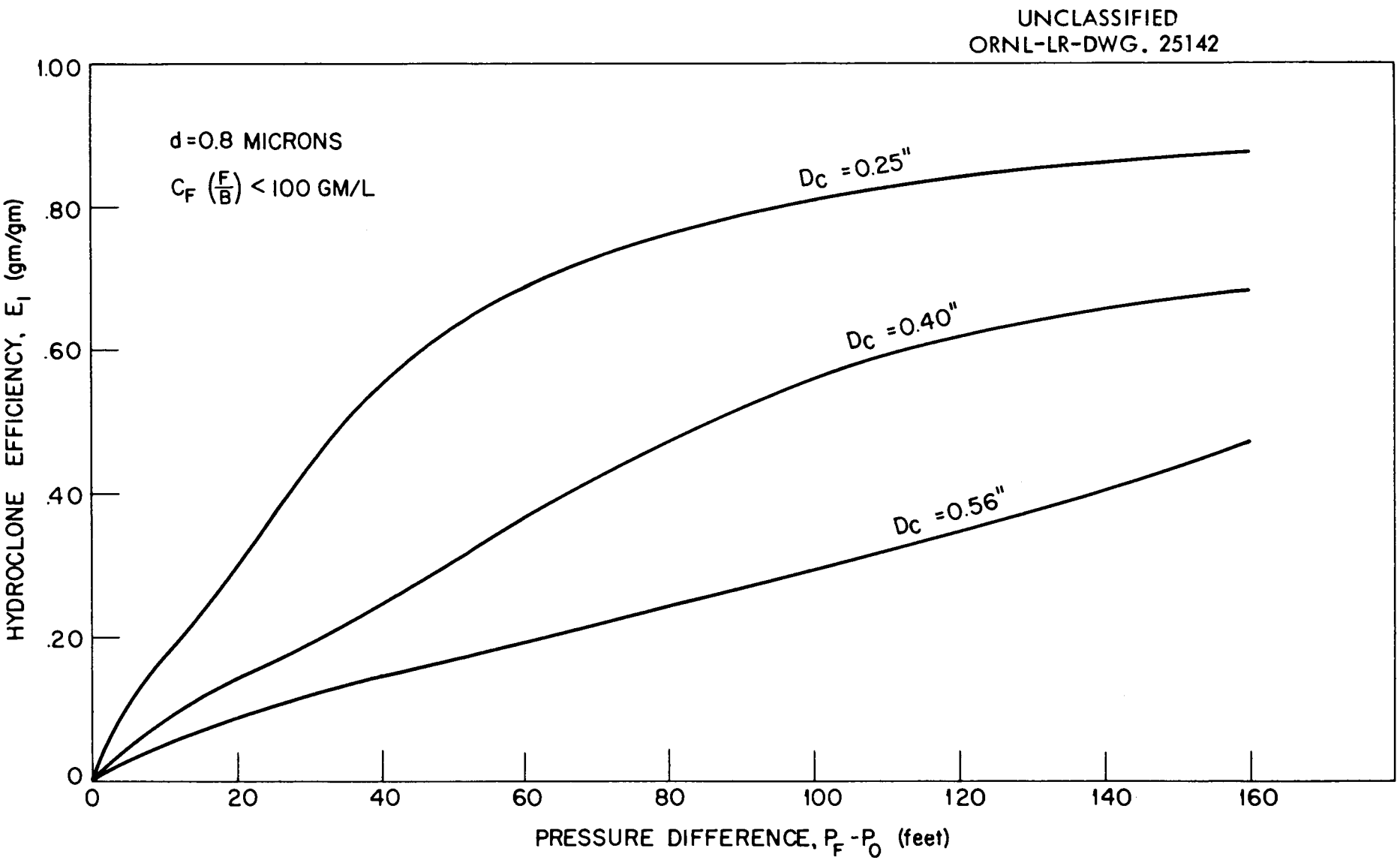


Fig.15. Hydroclone Efficiency vs Pressure Drop.

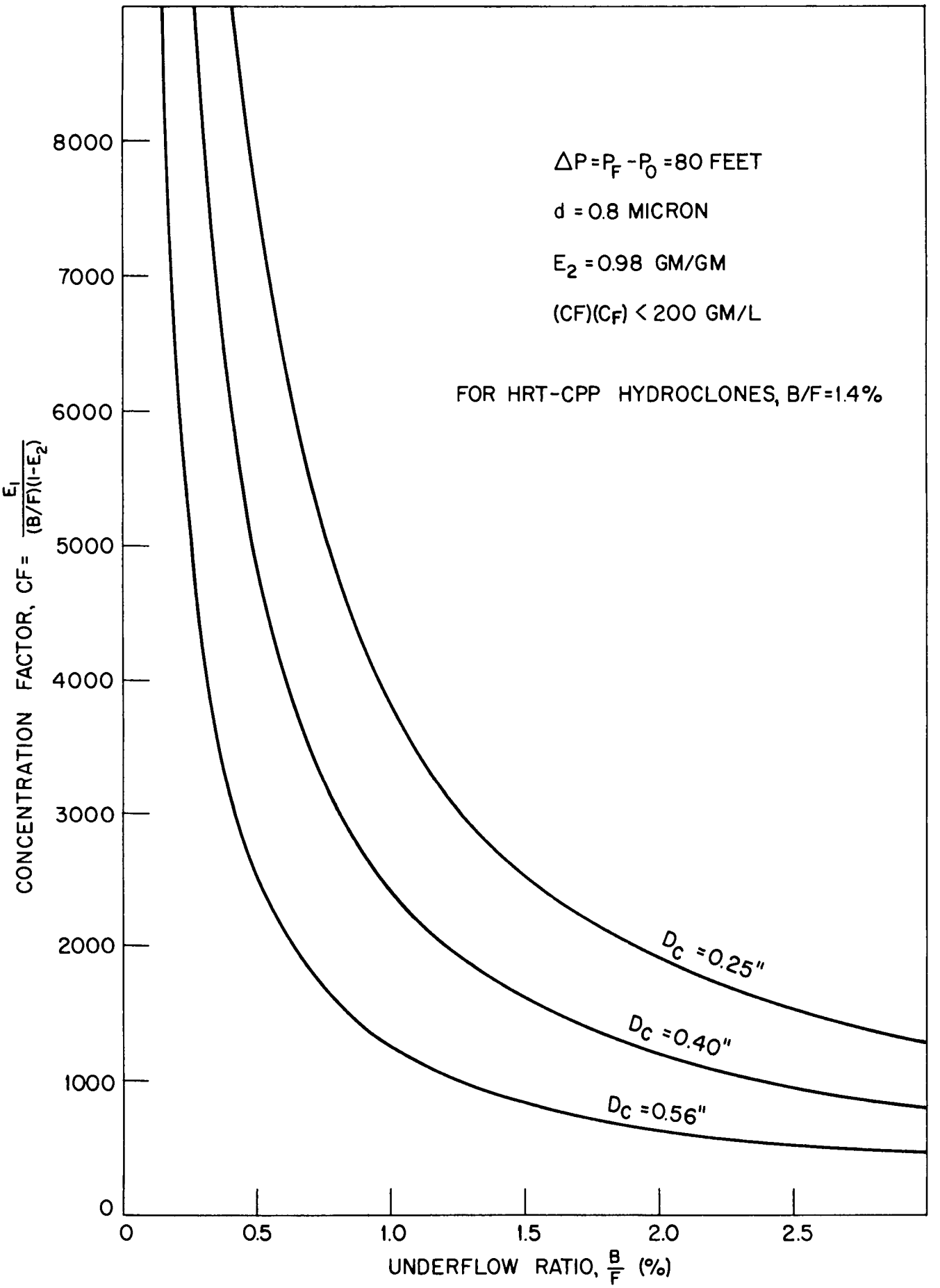


Fig. 16. Hydroclone Concentration Factor vs Underflow Ratio.

UNCLASSIFIED
ORNL-LR-DWG. 25144

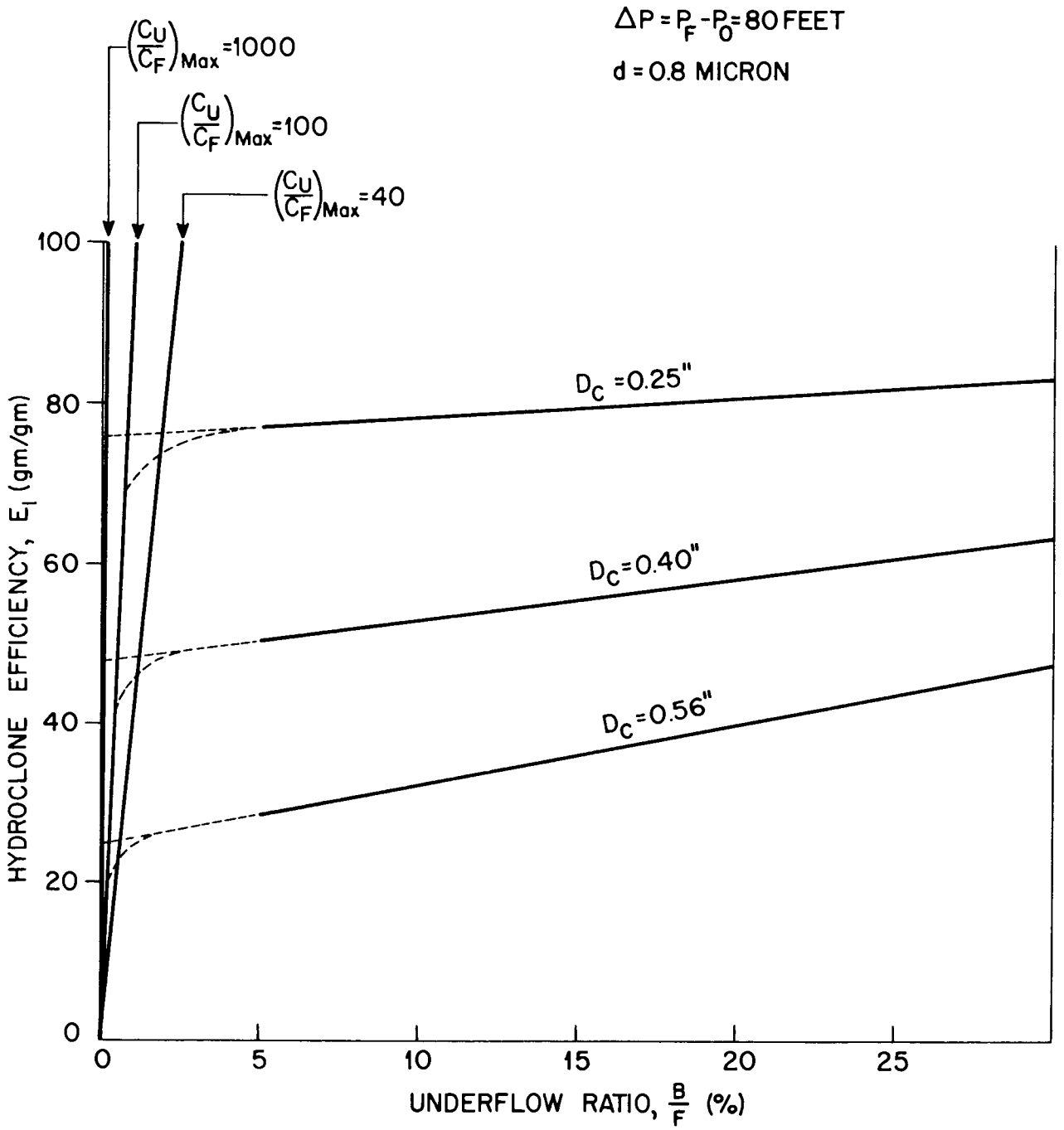


Fig. 17. Hydroclone Efficiency vs Underflow Ratio.

Table 6. Dimensions of HRT-CPP Hydroclones

Symbol	Location	Dimension (in.)		
D_c	Maximum inside diameter	0.25	0.40	0.56
L	Inside length	1.50	2.40	3.20
D_u	Underflow port diameter	0.070	0.100	0.148
D_o	Overflow port diameter	0.053	0.100	0.140
OD_o	Vortex finder diameter	0.073	0.150	0.170
L_o	Vortex finder length	0.188	0.188	0.250
H_f	Feed port height	0.063	0.110	0.180
W_f	Feed port width	0.033	0.100	0.110
D_f	Feed port effective diameter	0.051	0.118	0.159

Construction details are shown on the following ORNL drawings:

0.25 in. D_c - D-25074

0.40 in. D_c - D-24182

0.56 in. D_c - D-26412

Flanges - D-24182 or D-25074

Since the calculated values are for specific conditions, these conditions and certain implied limitations apply to these curves. The efficiencies and concentration factors calculated apply for dilute concentrations of solids and are decreased wherever the underflow stream solids concentration becomes high enough to hinder the discharge of the solids. This limit is expressed as C_f (F/B) <100 g/liter (Figs. 13-15) or as (CF)(C_f) <200 g/liter (Fig. 16). For the same reason, the hydroclone efficiency vs. B/F follows two curves (Fig. 17). As B/F approaches 1/1, or 100%, the efficiency also approaches 1, or 100%, along a straight line which goes between an efficiency of 100% at B/F = 100% and the efficiency for infinitely dilute feed as B/F approaches zero (E_{1_o}). For any finite feed concentration, E_1 is zero when B/F is zero and the efficiency approaches zero along a line which is determined by the maximum rate at which the underflow stream can remove the concentrated solids. Three such lines representing C_u/C_f of 1000, 100, and 40 are shown in Fig. 16. The limiting underflow concentration and the behavior of E_1 as this concentration is approached are not known, but they should be functions of the feed concentration and the properties of the suspended solids.

The combinations of hydroclone variables calculated and presented were selected from many possible combinations as being the most useful for HRT Chemical Plant applications. The capacity vs. pressure drop curves can also be represented by equations:

$$\Delta P\ (D_c = 0.25) = 3600\ F^{2.35} \tag{17}$$

$$\Delta P\ (D_c = 0.40) = 198\ F^{2.27} \tag{18}$$

$$\Delta P\ (D_c = 0.56) = 57\ F^{2.27} \tag{19}$$

where ΔP is the feed-to-overflow pressure drop in feet of liquid and F is the feed flow rate in gallons per minute.

The hydroclone efficiency vs. particle size curves can be reduced to a general curve by plotting d/d_{50} instead of d as the abcissa. Agglomeration of particles, with a resulting increase in efficiency, increases as the particle size decreases and is very pronounced for diameters below 1 micron. The hydroclone may therefore "see" an effective diameter which is larger than the diameter of discrete, individual particles. The concentration ratios (Fig. 16) should be considered chiefly as relative values for the hydroclones since the value of 1 - E_2 is not known with any accuracy. Values of E_2 of 0.96 or 0.99 would halve or double the concentration factor and a value of 0.80 would decrease it by a factor of 10.

7.0 REFERENCES

1. R. A. McNees. "The Chemical Behavior of Some Fission and Corrosion Products in Uranyl Sulfate Solutions at Elevated Temperatures," 2nd annual meeting of American Nuclear Society, Session XIII, June 7, 1956.

2. D. F. Kelsall. "A Study of the Motion of Solid Particles in a Hydraulic Cyclone," Trans. Inst. Chem. Eng. London, 30, 87-108 (1952).

3. D. F. Kelsall. "A Further Study of the Hydraulic Cyclone," Chem. Eng. Sci., 2; 254-272 (1953).

4. N. Yoshioka and Y. Hotta. "Liquid Cyclones as a Hydraulic Classifier," Chem. Eng. Japan, 19; 632-640 (1955).

5. D. A. Dahlstrom. "Cyclone Operating Factors and Capacities on Coal and Refuse Slurries," Trans. Am. Inst. Min. Eng. 184, 331-344 (1949).