MAR 23 1960

MASTER

ORNL-2876
UC-4 - Chemistry-General

SOLIDS SEPARATION BY A HYDRAULIC CYCLONE
WITH A BATCH UNDERFLOW RECEIVER

P. A. Haas

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in USA. Price \$1.50. Available from the
Office of Technical Services
Department of Commerce
Washington 25, D.C.

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, expressed 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, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL-2876

Contract No. W-7405-eng-26

CHEMICAL TECHNOLOGY DIVISION

Unit Operations Section

SOLIDS SEPARATION BY A HYDRAULIC CYCLONE

WITH A DATCH UNDERFLOW RECEIVER

P. A. Haas

DATE ISSUED

MAR 18 1960

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
Operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION

ABSTRACT

Engineering correlations based on experimental studies are presented for the application of batch accumulation of solids separated from solid-liquid feed to a cyclone. This method of cyclone operation simplifies the problem of flow control involved with continuous underflow. The efficiency and capacity correlations for hydroclones with continuous underflow also apply to this type of operation. The volume flow exchanged with the underflow receiver may be varied from 0.2 to 6% of the feed flow volume by varying the hydroclone dimensions. Minimum ratios of the feed to underflow receiver concentrations can be predicted, and values of up to 10^4 were obtained experimentally. This technique was used for both the concentration of solids and the clarification of the liquid phase with hydroclones in the size range of 0.16 to 3.5 in. dia.

CONTENTS

	Page
1.0 SUMMARY	1
2.0 INTRODUCTION	2
3.0 DEVELOPMENT OF THEORY	2
3.1 Nomenclature	4
3.2 Induced Underflow Ratio	6
3.3 Recycle Efficiency	7
3.4 Concentration Factors	8
4.0 DISCUSSION OF EXPERIMENTAL RESULTS	9
4.1 Hydroclone Dimensions, Efficiencies and Capacities	9
4.2 Experimental Underflow Ratios	13
4.3 Experimental Recycle Efficiencies	16
4.4 Experimental Concentration Factors	18
4.5 Effects of High Slurry Concentrations	20
4.6 Multiple Hydroclone Systems	22
5.0 APPLICATIONS	24
5.1 Dilute Slurry Feeds	24
5.2 Concentrated Slurry Feeds	25
6.0 REFERENCES	33
7.0 APPENDIX	34
7.1 Derivation of Induced Underflow Equations	34
7.2 Experimental Data for Underflow Ratio Determinations	37

1.0 SUMMARY

For a method of operation analogous to batch dust collection by a gas-solid cyclone, the use of an induced underflow receiver for batch accumulation of the heavy phase by a liquid-solid cyclone was evaluated experimentally and by calculations. Procedures were devised to experimentally determine the critical factors defined as the underflow ratio and the recycle efficiency.

Results for 0.16- to 3.5-in.-dia hydraulic cyclones include (for nomenclature as defined in Sec. 3.1):

- (a) Confirmation of previously developed efficiency and capacity correlations including:

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

$$\Delta P = 0.07 \frac{F^{2.27}}{D_c^{0.8} D_F^{1.3} D_o^{2.0}}$$

- (b) Induced underflows into the receivers of 0.2 to 6.0% of the hydroclone throughput correlated by:

$$\frac{B}{F} = 23 \frac{\Delta P^{0.25} D_u^{1.8} D_c^{2.0}}{L^{3.0}}$$

- (c) Experimental recycle efficiencies, E_2 , consistent with:

$$E_2 = 2E_1 - E_1^2$$

- (d) Concentration ratios of the underflow receiver concentration to the feed concentration of up to 10^4 .

This method of operation was applied successfully to both dilute and concentrated slurry feeds to avoid the inventory and flow control problems associated with continuous discharge of an underflow stream. Thus application of hydraulic cyclones or hydroclones was practical for aqueous homogeneous reactor fuel systems (dilute corrosion product slurries) and blanket systems (ThO_2 slurries of up to 1500 g $\text{ThO}_2/\text{kg H}_2\text{O}$).

2.0 INTRODUCTION

Discussion of a theory and supporting experimental data resulting from studies of "induced" underflow operation of hydraulic cyclones or hydroclones are presented in this report. Both theoretical and experimental studies have been reported for application of hydraulic cyclones or hydroclones to split a two-phase feed fluid into an overflow stream depleted of a heavy phase and an underflow stream in which the heavy phase is concentrated.¹⁻⁵ The fraction of the feed volume discharged to the underflow stream, and thus the concentration in the underflow stream, may be controlled by the construction of the hydroclone or by throttling devices. For many applications of hydroclones, the underflow stream containing the concentrated heavy phase is simply accumulated. Metering, controlling, and collecting of this concentrated stream is often difficult and inconvenient, especially if it is a concentrated slurry of solids. Batch accumulation of the heavy phase in an underflow receiver in a manner similar to dust collection for gas-solid cyclones eliminates controlling and handling this stream. An application of this method of operation was reported previously.⁶ Studies of batch dust accumulation for gas-solid cyclones have been chiefly of an empirical nature limited to configurations to ensure dust discharge.

Differential material balances were developed and simplified to obtain equations applicable to "induced" underflow operation; then the constants were determined and the equations verified by experimental studies. A consistent nomenclature was defined and applied with the recognition that it contains some implied assumptions. Sufficient experimental data were obtained to indicate what configurations favored optimum performance and what performance could be expected. Results are included for induced underflow accumulation with both dilute and concentrated slurry feed streams.

Ideas and experimental data originated by a number of people have been incorporated in this report. Early development studies by M. E. Whatley and J. R. Engel and studies with concentrated ThO_2 slurries by J. W. Snider merit particular acknowledgment.

3.0 DEVELOPMENT OF THEORY

Accumulation of the heavy phase in an underflow receiver, a cavity into which the hydroclone underflow port opens (Figure 3.1), is a useful alternative 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 the particles were not too small to settle faster than convection flows from thermal or density gradients.

Fig. 3.1. Induced underflow receiver nomenclature.

The simplest underflow receiver geometry is a chamber of at least 10 times the hydroclone volume with the hydroclone underflow port flush with one wall. Baffles within the chamber or a connecting channel of diameter less than the hydroclone diameter restrict the induced underflow and make analyses of results more difficult.

The flows and concentrations involved in the collection of suspended solids in an induced underflow receiver are elusive and difficult to measure. Variations in definitions could produce several individually consistent sets of analyses and expressions for performance factors. The definitions selected for this report result in expressions which can be verified or evaluated experimentally. The results of the derivations and their meanings are presented in succeeding sections; the detailed derivations are given in the appendix.

3.1 Nomenclature

The nomenclature defined below is used throughout this report. The location of flows and their concentrations are shown on a schematic drawing of a hydroclone with an induced underflow receiver. (Figure 3.1) The units applicable to the empirical constants determined are listed with these constants; any consistent units may be substituted in the other equations.

B = Volume rate of the induced underflow either as the volume rate of flow into the underflow receiver or the volume rate from the underflow receiver to the overflow stream

B_r = Recycle rate of fluid from the underflow receiver to the hydroclone and back to the underflow receiver without any effective separation due to the centrifugal field

C_b = Underflow stream concentration

C_f = Feed stream concentration

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

C_o = Overflow stream concentration

C_{sb} = Concentration of a settled bed under gravity

CF and CF_{eq} = Concentration ratios defined as C_p/C_f at any time and C_p/C_f at equilibrium time, respectively.

D_c = Inside diameter of the hydroclone at the feed port, i.e., the maximum i.d.

- D_f = Diameter of a circle of area equal to the feed port area
- D_o = Overflow port diameter, i.e., the vortex finder i.d.
- D_u = Underflow port diameter
- d = Apparent Stokes diameter of a solid particle
- d_{50} = Apparent Stokes diameter of a particle removed with 50% efficiency; i.e., $E_o = 50\%$
- E_o = Separation efficiency of the hydroclone, i.e., the fraction of the feed stream solids which appear in the underflow stream in addition to that which would appear due to the volume fraction to the underflow
- E_1 = Hydroclone efficiency or the fraction of the solid particles in the feed stream which is discharged with the underflow stream
- E_2 = Recycle efficiency for returning to the underflow receiver the solids in the stream from the underflow receiver to the overflow stream. This efficiency is defined mathematically by Eq. 3.
- F = Volume flow rate of feed
- H_f = Height of feed port
- K and K' = Empirical constants
- L = Inside length of hydroclone from top of feed port to underflow port
- L_o = Length of vortex finder below the top of the feed port
- L_{Ch} = Length of a small-diameter channel (diameter less than D_c) connecting the underflow port and the induced underflow receiver
- L_t = Sum of $L_{Ch} + L$
- OD_o = Outside diameter of vortex finder extending down into hydroclone
- ΔP = Pressure drop from feed line to overflow line
- P_f = Feed line pressure
- P_o = Overflow pressure

P_u = Underflow line pressure or the induced underflow receiver pressure

R = Apparent efficiency or recycle efficiency for induced underflow operation equal to $(C_f - C_o)/C_f$

S = Amount of material in underflow receiver; for a homogeneous receiver $S = V_p C_p$

V_p = Volume of induced underflow receiver

W_f = Width of feed port

z = Dimensionless constant

μ = Fluid viscosity

ρ_l = Fluid density

ρ_s = Solid particle density

θ = Time

3.2 Induced Underflow Ratio

The volume flow rate from the hydroclone into the underflow receiver is characteristic of this type of operation and controls the performance. If this rate is too small, the concentrated heavy phase will not be transferred to the underflow receiver at the rate at which the hydroclone normally collects it. If the rate is too large, this stream will not be concentrated enough and the underflow receiver concentration will be limited. This rate can be most conveniently expressed as its ratio to the volume feed rate, written B/F , in order to minimize or eliminate some of the variables that affect both rates in the same way.

Expressions for this "induced underflow ratio," the recycle efficiency, E_2 , and the concentration factors CF_{eq} , C_o/C_f , C_o/C_p , and C_p can be derived from the following material balance equations:

$$FC_f + BC_p = BC_b + FC_o \quad (1)$$

$$dS = F (C_f - C_o) d\theta \quad (2)$$

$$BC_b = FC_f E_1 + BC_p E_2 \quad (3)$$

Other assumptions, such as $S = V_p C_p$ and that B/F is not a function of concentrations, are involved in some of the derivations.

The material balance of Eq. 1 can be reduced to the following expression for a soluble salt (initial concentration of C_{po}) in the induced underflow receiver and a salt-free feed to the hydroclone ($C_f = 0$):

$$\frac{B}{F} = \frac{C_o}{C_p} = \frac{C_{\infty}}{C_{po}} \quad (4)$$

For a homogeneous underflow receiver with $S = V_p C_p$ and the conditions above, Eqs. 2 and 4 can be combined and integrated:

$$\frac{B}{F} = \frac{V_p}{F(\theta_2 - \theta_1)} \ln \left(\frac{C_{o1}}{C_{o2}} \right) \quad (5)$$

3.3 Recycle Efficiency

Solids enter the hydroclone in the induced underflow stream from the underflow receiver, and the efficiency with which these solids are recycled to the underflow receiver is important to the performance obtained. This recycle efficiency is defined by

$$FC_o = FC_f(1 - E_1) + BC_p(1 - E_2) \quad (6)$$

The $FC_f(1 - E_1)$ term gives the amount of feed stream solids that do not reach the underflow receiver and the $BC_p(1 - E_2)$ term gives the amount of solids from the underflow receiver that find their way to the overflow stream. The values of E_2 may be determined by using pure water feed to a hydroclone with a homogeneous slurry in the induced underflow receiver. The overflow stream is sampled periodically to obtain a C_o versus time curve. If C_{po} is known, a value of C_{∞} , determined by extrapolation to zero time, may be used to calculate E_2 :

$$E_2 = 1 - \frac{FC_o}{BC_p} = 1 - \frac{C_{\infty}/C_{po}}{B/F} \quad (7)$$

If the agitation is adequate to maintain a homogeneous slurry in spite of dilution at the underflow port, E_2 may be calculated from the C_o versus time curve and the equation:

$$E_2 = 1 - \frac{V_p}{B(\theta_2 - \theta_1)} \ln \frac{C_{o1}}{C_{o2}} \quad (8)$$

Experimentally determined values of CF_{eq} may also be used to obtain values of E_2 .

The values of E_2 would intuitively be expected to be a function of E_1 since both efficiencies are a measure of the centrifugal fields of the hydroclone. Consider a power expansion of E_1 as an empirical expression of E_2 :

$$E_2 = a(E_1)^0 + bE_1 + cE_1^2 + dE_1^3 + \dots \quad (9)$$

Some logical restrictions on the values of the constants for small values of B/F can be obtained from the following:

- (a) When $E_1 = 0$, $E_2 = 0$; therefore $a = 0$.
- (b) When $E_1 = 1.00$, $E_2 = 1.00$; therefore $b + c + d + \dots = 1.00$
or $c = 1 - (b + d + \dots)$.
- (c) Values of E_2 will be larger than the corresponding values of E_1 since the recycle stream enters at a more favorable point for separation (for low values of B/F).
- (d) For all values of E_1 between 0 and 1, E_2 must be between 0 and 1. This means that since $\partial E_2 / \partial E_1 = b$ for $E_1 = 0$, b must be positive and greater than 1. Also, $\partial E_2 / \partial E_1 = (b + 2c + 3d \dots)$ for $E_1 = 1$ where $0 \leq (b + 2c + 3d + \dots) \leq 1.00$. Subtracting the equality of b gives the result $-1 \leq (c + 2d + 3e + \dots) \leq 0$.
- (e) E_2 would not be expected to have any maximums or minimums other than at $E_1 = 0$ or $E_1 = 1$; i.e., the value of E_2 increases uniformly with E_1 .

From the above restrictions it is apparent that the higher powers of E_1 do not contribute significantly to the values of E_2 for $0 \leq (E_1 \text{ or } E_2) \leq 1$. Also, the limited data available would not justify any equation more complex than a quadratic for which the constants must be $a=0$, $b=n$, $c = b - 1 = n - 1$ to give:

$$E_2 = nE_1 - (n - 1)E_1^2 = E_1 + (n - 1)(E_1 - E_1^2) \quad (10)$$

where $1 \leq n \leq 2$. This restriction on n is derived from restriction d since $0 \leq [n - 2(n - 1)] \leq 1$.

3.4 Concentration Factors

An equilibrium concentration ratio between the feed concentration and the concentration of the induced underflow receiver at the underflow port may be calculated by noting that $C_f = C_0$ and $dS = 0$:

$$CF_{eq} = \left(\frac{C_p}{C_f} \right)_{eq} = \frac{F}{B} \left(\frac{E_1}{1 - E_2} \right) \quad (11)$$

This ratio gives a minimum value to which the heavy phase can be concentrated. Any settling in the induced underflow receiver will improve the concentration that can be obtained since C_p is the concentration of the flow from the underflow receiver into the hydroclone.

If a homogeneous underflow receiver is assumed, an expression can be derived for the receiver concentration as a function of time:

$$C_p = \frac{E_1}{1 - E_2} \left(\frac{C_f F}{B} \right) \left[1 - \exp \frac{-B}{V_p} (1 - E_2) \theta \right] \quad (12)$$

$$dS = V_p \frac{dC_p}{d\theta} = E_1 C_f F \exp \left[\frac{-B}{V_p} (1 - E_2) \theta \right] \quad (13)$$

4.0 DISCUSSION OF EXPERIMENTAL RESULTS

The experimental results were organized to demonstrate and verify the B/F, E_2 , and CF_{eq} derivations presented in Sect. 3. Values of E_0 and E_1 are presented. The effects of slurry concentrations and the concentrations at which these effects appear are discussed. The induced underflow type of operation was initially studied for application to very dilute corrosion product slurries for the chemical processing of aqueous homogeneous reactors.⁶ For this application induced underflow eliminated the extremely difficult flow control and metering problems found with continuous underflow. The studies with concentrated slurries were made to permit effective application to engineering studies of high-pressure aqueous thorium slurries. Complete slurry transfer during experimental studies was not possible by a simple transfer of fluid. Inventory and waste problems were greatly simplified by recycling clarified water from the hydroclone overflow instead of introducing wash water.

4.1 Hydroclone Dimensions, Efficiencies, and Capacities*

Based on experimental studies made with hydroclones of diameters less than 1 in., the following dimensions are recommended as giving the maximum efficiencies for a given ΔP and hydroclone diameter:

Symbol	Dimensions Nomenclature	Sizes as Fraction of D_c	
		Possible Range	Recommended for Induced Underflow Operation
D_c	Hydroclone i.d. at feed port	1	1
L	Hydroclone inside length	5-8	6
D_f	Feed port diameter	1/3 - 1/7	1/4
D_u	Underflow port diameter	1/3 - 1/6	1/4
D_o	Overflow port diameter or vortex finder i.d.	1/4 - 1/6	1/5
OD_o	Outside diameter of vortex finder extension into hydroclone	1/3 - 1/6	1/4
L_o	Length of vortex finder below top of feed port	1/3 - 1/2	3/8

*The results in this section as previously reported by the author⁶ are also applicable to hydroclones with continuous underflow; they are repeated to give a complete treatment of the performance of hydroclones with induced underflow.

These values are consistent with literature values^{2,5} recommended for 3- to 6-in.-dia hydroclones. The feed port dimension is given as a diameter, but rectangular feed ports are desirable with the area the same as those of circular ports of the diameters suggested.

The efficiencies and capacities of hydroclones of less than 1-in. dia, dimensional ratios within the possible range for efficient operation as listed above, and ΔP of over 20 ft may be correlated with the fluid properties and the hydroclone dimensions by:

$$d_{50} = 5 \times 10^3 \frac{D_c^{0.5} \mu^{0.5}}{(\Delta P)^{0.25} (\rho_s - \rho_l)^{0.5}} \quad (14)$$

$$\Delta P = 0.07 \frac{F^{2.27}}{D_c^{0.8} D_f^{1.3} D_o^{2.0}} \quad (15)$$

where diameters are in inches, fluid viscosity in pounds per foot per second, pressure drop in feet, densities in pounds per cubic foot, and feed rate in gallons per minute. The efficiency correlation [eq. 14 also presented as a nomograph (Figure 4.1)] cannot be extrapolated to agree with efficiencies for above 3-in.-dia hydroclones; Eq. 15, however, agrees well with the experimental curve for a 3.5-in.-dia hydroclone and with the literature values^{2,5} for 3- to 6-in.-dia hydroclones. For the dimensions listed as recommended for induced underflow operation, eq. 15 reduces to:

$$F = 0.37 (\Delta P)^{0.44} D_c^{1.8} \quad (16)$$

The separation efficiency is obtained by using the calculated values of d_{50} in conjunction with reduced efficiency curves (Figure 4.2). Results at ORNL with 0.4- and 0.5-in.-dia hydroclones confirm the difference in reduced efficiency curves reported by Bradley⁹ and shown in Figure 4.2 for 10-mm-dia hydroclones as compared to 3- to 6-in.-dia hydroclones.

The value of E_1 is calculated from the values of E_0 and B/F :

$$E_1 = E_0 + \frac{B}{F} (1 - E_0) \quad (17)$$

The term $B(1 - E_0)/F$ gives the amount of solids transferred to the underflow stream due to its volume without any separation by the hydroclone.

Correlations of hydroclone efficiency with the hydroclone dimensions and the fluid properties in the form of Eq. 14 can be obtained with an undetermined constant from theoretical models of several types. A correlation similar to Eq. 15 has also been developed theoretically.⁵ If conservation of momentum is assumed, an experimental constant smaller than 5 by 10^3 is obtained for Eq. 14. The size of the constants in

Fig. 4.1. Correlation of hydroclone efficiencies with operating conditions.

Fig. 4.2. Reduced efficiency curves for hydraulic cyclones.

Eqs. 14 and 15 for a particular hydroclone is a measure of how well it is dimensioned and fabricated. Values greater than 5×10^3 for Eq. 14 and smaller than 0.07 for Eq. 15 consistently go together and indicate an inefficient design in some respect and a lowered centrifugal field. It is obvious that a decrease in centrifugal field will increase the d_{50} . From one viewpoint, the major part of the pressure drop is the difference in fluid head across the centrifugal field. Thus any turbulences which dissipate energy and reduce the centrifugal field will actually increase the capacity. It is probable that most of the internal fins and baffles sometimes recommended for increasing the capacities of large-diameter gas cyclones actually reduce the separation efficiencies.

Correlations of d_{50} and ΔP have been reported from experimental results for both large-diameter^{1,3,5} and small-diameter^{4,8,9} hydroclones. Results for hydroclone capacity by several authors^{2,5,8} agree well with the empirical constant given for Eq. 15. A combination of higher capacity and lower efficiency, as reported⁴ for 10- to 50-mm-dia glass hydroclones,⁴ is probably due to energy losses, perhaps as a result of feed port irregularities.

4.2 Experimental Underflow Ratios

A satisfactory dimensionless correlation of the experimental induced underflow rates could not be found and the following empirical expression is recommended for B/F ratios of less than 0.06:

$$\frac{B}{F} = 23 \frac{p^{0.25} D_u^{1.8} D_c^{2.0}}{L^{3.0}} \quad (18)$$

This expression was determined for and is considered valid under the following conditions:

B/F	0.002 to 0.6	D_c	0.16 to 4 in.
ΔP	> 20 ft	L/D_c	5 to 8
D_u/D_c	< 0.4		

This equation is presented in Figure 4.3 as a nomograph with $\Delta P = 100$ ft. This correlation is limited to conical hydroclone geometry and unbaffled underflow receiver as previously described. The experimental values from which Eq. 18 was derived are tabulated in the Appendix (Tables 7.1 and 7.2, Figure 7.1). The induced underflow is due to pressure drops which are small compared to the pressure drop from the feed to overflow and can be greatly changed by geometry changes which have little effect on the other performance characteristics of the hydroclone.

The initial examination of the underflow ratio data was from a dimensionless analysis viewpoint with D_u , D_c , and L_t as the variables to give:

UNCLASSIFIED
ORNL-LR-DWG-35021

Fig. 4.3. Correlation of induced underflow ratio with hydroclone dimensions.

$$\frac{B}{F} = z \left(\frac{D_u}{D_c} \right)^a \left(\frac{D_c}{L_t} \right)^b = z D_u^a D_c^{b-a} L_t^{-b} \quad (19)$$

This expression would give equal B/F values for dimensionally similar hydroclones independent of pressure drops. However, z was found to be a function of both D_c and ΔP .

The form of Eq. 18 was selected from the observation that the experimental data gave values of z in Eq. 19 that could be expressed by

$$z = \text{constant } (\Delta P)^{0.25} D_c^{0.8}$$

All the hydroclones of less than 1-in.-dia were fabricated to have internal surface finished of about 6 μ in. while the 3.5-in.-dia unit had a finish of about 20 μ in. If B/F was proportional to the surface roughness raised to the power e and e was about -1, B/F could be written as a dimensionless correlation. Such a relation appears logical, but data on the effects of surface roughness are not available. Also, limited data on scaling and corrosion caused by operation with aqueous solutions at 250 to 300°C did not indicate any large changes in B/F.

Correlation of the induced underflow ratio, instead of the value of B by itself, was intended to minimize the dependence on D_c and ΔP . For values of $D_u = 0.25D_c$ and $L = 6D_c$, Eq. 18 becomes:

$$B = 0.0088 (\Delta P)^{0.25} D_c^{0.8} F \quad (20)$$

Equation 16 for these dimensions was:

$$F = 0.37 (\Delta P)^{0.44} D_c^{1.8}$$

Substituting,

$$B = 0.00325 (\Delta P)^{0.69} D_c^{2.6}$$

Since the fluid densities vary with concentration, the values of B/F desired would be for C_p and C_b to give solutions of equal densities since these concentrations would be equal at equilibrium. A pronounced effect of density on B/F was found when results for varying concentration were substituted in Eq. 5 while B/F values from Eq. 4 showed less sensitivity to concentration; i.e., density (Tables 7.1 and 7.2). Fluid density differences at the underflow port may increase or decrease B/F depending on whether they add or subtract from the pressure differences causing the induced underflow.

The values of B/F were obtained chiefly by the use of C_o values extrapolated to zero time with Eq. 4 (Figure 7.2). Values obtained by

this method were about 0.6 of the values from the slope of $\log C_0$ versus θ curves (Figure 7.3) and Eq. 6. Both procedures were with from 500 to 30,000 ppm of lithium as LiCl in the induced underflow receiver. When C_{∞} was to be determined by extrapolation to zero time, overflow stream samples were taken at measured times after a startup during which the feed flow was established as smoothly and rapidly as possible.

The observed differences between the two methods of B/F measurement would be expected from the probable sources of error. If mixing in the induced underflow receiver is incomplete, C_p is less than instead of equal to S/V_p . Calculations of B/F from Eq. 5 thus use a V_p which is larger than the true volume of mixed solution, and the values of B/F will be too large. If the experiment is continued long enough, the presence of unmixed regions of concentrated solution will make themselves apparent by a flattening of the $\log C_0$ versus time curve. The final result would be an extremely low B/F value, with the true value at some indeterminate point. This type of curve was obtained for some tests where overflow stream concentrations were sampled for ranges of 10^2 to 10^4 . The effects of initial flow irregularities on the values of C_{∞} used in Eq. 4 are not easily detectable. The most probable effect is low values of B/F since the extrapolation to zero time may be made from points which give low values for the slope.

Density effects would cause errors for either procedure (see Sec. 7.1) but would probably be more important for the complete mixing assumed for Eq. 6. Both experimental and theoretical considerations indicate that the correct B/F values are much nearer the results from Eq. 4 than those from Eq. 6. The results indicate the variations to be expected from hydroclone dimension variations.

4.3 Experimental Recycle Efficiencies

A value of $n = 2$ for Eq. 10a to give Eq. 10b adequately represented the experimental values for E_2 :

$$E_2 = nE_1 - (n - 1) E_1^2 \quad (\text{Eq. 10a})$$

$$E_2 = 2E_1 - E_1^2 \quad (\text{Eq. 10b})$$

Calculated values of E_2 as a function of E_1 from Eq. 10, with n as a parameter, were compared with experimental points (Figure 4.4) to indicate the probable values of n . For application of Eq. 11 to calculations of values of CF_{eq} , settling or lack of mixing in the induced underflow receivers will produce errors an order of magnitude greater than those from a lack of precision in E_2 .

As compared to the induced underflow ratio, values of E_2 are difficult to obtain due to the sampling and mixing problems. The overflow stream solids concentration will be of the order of 1% of those of the

UNCLASSIFIED
ORNL-LR-DWG 40286

Fig. 4.4. Correlations of E_2 with E_1 and some experimental values of E_2 and E_1 . o experimental values using C_0 vs time curves with Eq. (7) or (8); • experimental values using equilibrium concentration factors and Eq. (11).

underflow receiver. Accurate sampling and analysis of slurry concentrations over this size range is difficult, especially since the density of the receiver slurry cannot be greatly different from 1 without affecting the value of E_2 obtained. The expressions derived for E_2 require uniform receiver slurry concentrations at the start for Eq. 7 and throughout the test for Eq. 8. Complete mixing at the start is difficult, and it becomes more difficult during operation with the resulting dilution at the underflow port.

4.4 Experimental Concentration Factors

Experimental concentration factors in agreement with Eq. 11 were obtained for agitated underflow receivers; values calculated from Eq. 11 are maximum values which may be exceeded due to settling in unagitated underflow receivers. Use of the calculated equilibrium concentration factor is usually of limited value for actual applications. The C_p is the concentration at the hydroclone underflow port and is usually not an average pot concentration because of the lack of mixing and the effects of settling. The efficiencies may be calculated for dilute slurries but become uncertain for high slurry concentrations. Even though the feed concentrations may be low, concentration factors of 10^2 to 10^4 result in high slurry concentrations at the induced underflow port. High slurry concentrations favor flocculation and thus promote settling. The maximum underflow receiver concentration possible is that of a settled bed. Therefore the actual observed underflow receiver equilibrium concentration will tend to be that of a settled bed with a region of lower concentration which is near the underflow port and is agitated by the induced underflow.

Experimental tests were made with agitated underflow receivers and dilute slurries in the induced underflow receivers and feed streams.¹³ The steady-state distributions of solids were determined in a small system consisting of the clone, a 73-ml magnetically agitated underflow pot, a 2-gal agitated feed tank, and 3 ft of connecting line which was 1/4-in. stainless steel tubing. The system was charged with 5 liters of water and about 0.5 g of ThO_2 and was run for 45 minutes (6 system displacements) before sampling. The data may be used to calculate either E_2 or C_p/C_f eq. Some results for this type of experiment (Table 4.1) show reasonably good agreement between the calculated and experimental concentration factors. The increasing disagreement with increasing mean diameters probably is due to increased settling in the receiver. The agreement between values of E_2 obtained directly and those obtained from CF_{eq} values (Figure 4.4) indicates that conditions to make the CF_{eq} equation valid were maintained.

Results for unagitated underflow receivers, some of which were designed to promote settling, demonstrate high concentration factors as compared to calculated CF_{eq} (Table 4.2). Some of these underflow receivers were glass pipes, and formation of settled beds of ThO_2 was easily visible. The induced underflow maintained an agitated region for about

6 in. below some hydroclone underflow ports. Baffles were effective in reducing this agitated region, but also tended to reduce the induced underflow ratio. Thermal convection from radiation heating might prevent settling for slurries containing fission products or irradiated thorium.

Table 4.1 Hydroclone Performance with Agitated Induced Underflow Receivers¹³

Hydroclone: $D_c = 0.25$, $L = 1.5$ in.

Operating conditions: H_2O at room temperature, $\Delta P = 80$ ft, $F = 0.20$ gpm

Induced underflow ratio, $B/F = 0.0198$

Agitation by magnetic stirrer

Slurry: $650^\circ C$ fired ThO_2

Mean ThO_2^a diameter, μ	E_1	E_2		C_{Feq}	
		From Eq. 8	From Eq. 7	$\frac{S}{V_p C_f}$	$\frac{R}{C_p(Calc)^b}$
1	26	52	49	35.6	26 (lowest)
1	29			37.5	31 (highest)
1.8	35	46	66	78	33 (lowest)
1.8	50			93	74 (highest)
4.1	95.8	90.1	94.0	2300	490 (lowest)
4.1	95.8	95.7	94.3	2420	1132 (highest)

^a 50 wt % smaller than this diameter.

^b Calculated from Eq. 11, using largest experimental values of E_2 to give highest values and smallest to give lowest values.

Table 4.2 Hydroclone Performance with Settling in Induced Underflow Receivers

Conditions: no mechanical agitation or thermal agitation by design in the induced underflow receiver

Hydroclone Diameters (D _c), in.	Material	Mean ^{a, b} Diameter, μ	Size Range, μ	Wt % within Size Range	Experimental ^c Concentration Factor [S/(V _p C _F)]
0.25	ZrO ₂	1.0	0 to 4.0	80	4500
0.40	Fe ₂ O ₃	0.5	0.2 to 0.6	80	270 ^d
0.40	ThO ₂	1.35	0.8 to 2.0	70	625
0.40	ThO ₂	1.0	0.6 to 2.0	80	1100
0.40	ThO ₂	1.0	0.7 to 1.5	80	1000
0.80	ThO ₂	1.1	0.5 to 2.0	80	1000
0.80	ThO ₂	1.1	0.5 to 2.0	80	500

^a50 wt % smaller than this diameter.

^bValues for samples in hydroclone feed at end of test.

^cEquilibrium was not attained at end of most tests.

^dBased on total iron in feed; a larger CF would result from use of insoluble iron as CF concentration.

4.5 Effects of High Slurry Concentrations

The values of the quantities used to characterize the induced underflow operation of hydroclones are changed when the hydroclones are applied to concentrated slurries. Qualitative observations of these changes were obtained from development studies for and applications to concentrated ThO₂ slurries. The characteristics and behavior of such slurries are so complex that generalized correlations of quantitative effects are probably not possible.

The efficiency of a hydroclone as the slurry concentration increases is affected by interactions between slurry particles. The effects of hindered settling and flocculation are surprisingly small, the interactions being minimized by the high shear in the hydroclones. The volume of the underflow stream may limit the rate at which the concentrated slurry can be discharged since this volume may be less than the physical volume of the slurry particles. This effect explains an apparent efficiency (calculated from feed and overflow stream concentrations) which decreases as the slurry concentration increases (Sec. 5.2, Figure 5.4). Thus the efficiency calculated from Eq. 14 and a reduced efficiency

curve is valid only for dilute slurries. The apparent efficiency,

$$(E_1)_{\text{apparent}} = \frac{B}{F} \left(\frac{C_{sb}}{2C_f} \right) \sim R$$

should be used whenever it is smaller than the E_0 from a reduced efficiency curve. The C_{sb} is the observed concentration for a bed from gravity settling of a slurry. This rough approximation for results with ThO_2 slurries (Sec. 5.2) is presented with the limitation that it may be less valid for other slurries.

The effects of slurry concentration on capacity at a given ΔP are not large if ΔP is expressed in feet of fluid. Where the change in slurry concentration through the hydroclone produces a significant density change, some average density, probably an arithmetic average of the feed and overflow densities, is required to give constants for Eqs. 15 and 16. This is consistent with the viewpoint that the pressure drop is accounted for by the fluid head of the centrifugal field. In addition to the varying density effect, higher slurry concentrations would tend to cause larger energy losses, lower centrifugal fields, and thus higher capacities. Dahlstrom¹ theorized that solids discharged with the underflow did not represent an energy loss in the vortex. On this basis he was able to obtain a capacity- ΔP correlation by reducing his feed flows to allow for these solids.

The main effect of high slurry concentrations on the induced underflow ratio is probably that due to the density differences. For the usual vertical upright position, the B/F ratio will be increased by the greater density of the underflow stream just as it is decreased by a greater density in the underflow receiver (Sec. 4.2). Since this effect will disappear as equilibrium is approached, it actually increases the effectiveness of induced underflow operation. This density effect is evident from the apparent efficiencies (see Sec. 5.2, Figure 5.4) for high slurry concentrations. For constant B/F values, the apparent efficiency would approach the B/F value as the concentration approached the maximum that could be discharged. Actually, the apparent efficiencies leveled out at values much higher than those for the B/F values measured with a soluble salt and zero slurry concentration. Some of these apparent efficiency values were 2 to 10 times the low-concentration B/F values.

The expressions for calculating E_2 and CF_{eq} have negligible application for concentrated slurries. While particle interaction to produce hindered settling and flocculation is minimized by shear in the hydroclone, it controls the slurry behavior in the induced underflow receiver. Baffles may be used to minimize the agitation by the induced underflow. Then if gas evolution, thermal convection, or other stirring effects are avoided, the slurry will settle to a normal bed density and the maximum pot concentration is that equivalent to the density of this bed. There will be a region around the underflow port which is agitated by the underflow stream.

4.6 Multiple Hydroclone Systems

Since the capacity of a single hydroclone may be limited by the small hydroclone diameter necessary to give the required efficiency, many applications require multiple hydroclone units. Test results (Table 4.3) indicate that several identical hydroclones can perform normally on a single underflow receiver while units of differing characteristics will have differing underflow ratios, and therefore poor performance. For extreme cases, such as for a plugged feed or overflow port, there could be a large flow through the underflow receiver entering through one or more underflow ports and leaving through the remainder of the ports. Such behavior might be difficult to predict or detect and might make multiple hydroclones on one underflow receiver undependable.

The results also indicate that small pressure variations due to unsymmetrical feed or overflow manifolding will cause large underflow ratio variations and poor performance for several hydroclones on a single underflow receiver. The last set of results in the table are for varying lengths of feed line to give feed pressures estimated to vary 1 to 2 ft for ΔP 's of about 70 ft. The results are consistent in that the high B/F values indicating large pot-to-hydroclone flows went with low efficiencies indicating small hydroclone-to-pot flows. The vertical hydroclone had the highest feed pressure and appeared to discharge a greater volume to the pot than was returned to it from the pot. The normal efficiencies of the 0.40-in.-dia hydroclone for $\Delta P = 100$ ft would be 30 to 45% for the ThO_2 used.

An experimentally tested procedure for the use of multiple hydroclones with induced underflow collection of the heavy phase is to feed a continuous underflow from multiple hydroclones (in parallel) to a single hydroclone on an underflow receiver. Continuous underflow rates of 3 to 30% of the feed flow are reasonable; therefore 3 to 35 single hydroclones may be put into parallel as the first stage. A flowsheet with thirteen 0.60-in.-dia hydroclones in parallel to feed their underflow to a 0.56-in.-dia hydroclone on an induced underflow receiver is in use in the Homogeneous Reactor Test Chemical Processing Plant (Sec. 5.1).

Table 4.3 Induced Underflow Ratios and Efficiencies for
Three Hydroclones on One Induced Underflow Receiver

Underflow receiver: two 2-in.-i.d. glass tees flanged together

Induced underflow determinations: by use of Eq. 4; $B/F = C_o/C_{po}$

Efficiency determinations: ThO_2 in H_2O at room temperature, 80 wt % of ThO_2 between 0.6 and 3.0 μdia

Pressure drops: $\Delta P = 100$ ft except as noted

Test Conditions	Hydroclones				Position	Experimental Efficiencies,		Experimental B/F,	
	D_c , in.	D_u , in.	L_t , in.	Calculated B/F, Eq. 18		%		%	
Identical hydroclones and identical feed pressures	0.40	0.100	2.40	0.0135	Vertical	-	-	0.0149	0.0149
	0.40	0.100	2.40	0.0135	Horizontal	-	-	0.0134	0.0157
	0.40	0.100	2.40	0.0135	Horizontal	-	-	0.0181	0.0219
	Averages							0.0155	0.0175
Duplicate of above with hydroclones interchanged	0.40	0.100	2.40	0.0135	Vertical	28.9	28.9 ^a	0.0171	
	0.40	0.100	2.40	0.0135	Horizontal	23.4	22.5 ^a	0.0162	
	0.40	0.100	2.40	0.0135	Horizontal	25.5	31.1 ^a	0.0149	
	Averages					26	28	0.0161	
Differing hydroclones with identical feed pressures	0.50	0.125	3.00	0.0140	Horizontal	15	22	0.0183	0.0183
	0.40	0.100	2.40	0.0135	Horizontal	21	13	0.0157	0.0157
	0.16	0.050	0.96	0.0090	Vertical	6	0	0.0002	0.0011
Identical hydroclones with ΔP 's differing by several percent	0.40	0.100	2.40	0.0135	Vertical	36.4 ^b	46.4 ^b	0.0086	
	0.40	0.100	2.40	0.0135	Horizontal	7.2 ^b	0.9 ^b	0.0288	
	0.40	0.100	2.40	0.0135	Horizontal	3.7 ^b	3.8 ^b	0.0535	
	Averages					16. ^b	17. ^b	0.0303	

^a $\Delta P = 45$ ft.

^bTotal feed-to-overflow pressure drop of 70 ft.

5.0 APPLICATIONS

The batch operation that results when induced underflow receivers are used with hydroclones has two advantages: (1) for dilute feed slurries where the volume of solids collected is small, further handling or disposal may be most conveniently done on a batch basis; (2) the control problems associated with metering a slurry stream and perhaps metering a stream to replace the volume discharged are eliminated. The second advantage is particularly important when the hydroclone is in a closed high-pressure loop and the underflow stream must be discharged to and replaced from atmospheric pressure. Both these advantages were obtained in the chemical processing of aqueous homogeneous reactor fuel solutions and the first was obtained in thorium slurry loops by accumulating the slurry in underflow receivers.

5.1 Dilute Slurry Feeds

Accumulation of insoluble fission and corrosion products in the induced underflow receiver of a hydroclone is the basic processing method for the Homogeneous Reactor Test fuel processing pilot plant.⁷ Solubility measurements indicated that removal of rare gases and insoluble fission products would leave about 2% as soluble salts and 12% in an undetermined state. The behavior of the insoluble fission products by themselves and in the presence of the predominant corrosion products was studied at reactor temperatures and pressures.¹⁰

Corrosion products were collected by the Homogeneous Reactor Test (HRT) chemical plant at average rates of 0.32 to 2.6 g/hr.^{11,12} The concentrations of circulating solids were very low and this removal of 1 to 10 ppm of corrosion products from the stream through the chemical plant probably represented essentially complete removal of insoluble material. The average underflow pot-to-feed concentration ratios exceeded 10,000, but settling in the underflow receiver probably prevented recycle of concentrated slurry through the hydroclone underflow port.

Initially only 10 to 25% of the corrosion products circulated long enough to be removed by the chemical plant. Although the fraction collected seemed to increase as operating time was accumulated, the average rates still appeared to be much below 100% after several thousand hours of reactor operation. Initially predicted solids production rates⁷ (Table 5.1) were probably reasonable estimates for normal operation. Two short periods of high corrosion occurred, one of which produced kilogram quantities of stainless steel corrosion products and the other kilogram quantities of ZrO_2 . The observed collection rates (Table 5.2) show much higher values for the collection periods immediately after reactor startups (Runs 16-1, 17-4, and 18-7). The compositions show the burst of zirconium corrosion and the insertion of a titanium sample holder.

Table 5.1 Predicted Solids Production in the HRT

Core power: 5 Mw

Corrosion rates: 1 mpy for stainless steel; 10 mpy for zirconium core tank

Material	Estimated Production, g/day	Estimated Composition of Suspended Solids, wt %
ZrO ₂	24	42
Fe ₂ O ₃	22	38
Cr ₂ O ₃	6	10
Rare earth sulfates	2.6	5
Other fission products	~3	5

The initial processing arrangement gave a fuel system inventory to processing rate ratio of 1.8 hr (Fig. 5.1a); alterations were made to decrease this to about 0.20 hr (Fig. 5.1b). Since several methods of calculation based on HRT experimental data indicate average circulation times of about 0.5 hr for corrosion products, the revised system should result in a higher collection efficiency. Actual collection rates after alteration were within the 3- to 6-fold increase range predicted by calculations.

A design was developed to permit replacement of a hydroclone in a radioactive system by use of a flanged closure and remote tools (Fig. 5.2). 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 can be removed and replaced by remote tools. This replacement might be required by a corroded or plugged hydroclone, or might be to obtain a different capacity, underflow ratio, or efficiency.

5.2 Concentrated Slurry Feeds

Hydroclones with induced underflow receivers have been applied to removal of ThO₂ slurries of high concentration circulating in closed systems. The important advantage for this application is the constant fluid inventory possible when induced underflow operation is used. If this constant inventory is not necessary, i.e., for an open system, the slurry can be more effectively concentrated and removed by use of a continuous underflow stream. As indicated in Sec. 4.5, the behavior of the slurry is affected by particle interactions. While hydroclone performance was correlated on the basis of the equivalent Stokes diameters and the particle densities for dilute slurries, additional slurry properties would have to be considered for concentrated slurries.

Table 5.2. Collection of Corrosion Products by the
HRT Chemical Processing Plant

Run No.	Operating Time, hr	Corrosion Products Collected, g	Avg. Rate, g/hr	Composition of Corrosion Products, %				
				Fe	Cr	Ni ^a	Zr	Ti
16-1	120	150	1.25	52	5	---	11	0
16-2	310	99	0.32	48	5	3	8	0
16-3	339	115	0.34	56	5	0	6	0
17-4	290	530	1.83	22	4	0	45	0.2 ^c
17-5	439	145	0.33	19	4	0.3	49	1
17-6	101	51	0.50	19	4	0	48	0.8
18-7	106	273 ^b	2.6	21	3	0.5	49	0.6
18-8	335	613	1.8	24	9	---	38	0.7

^aNickel should be completely soluble for these concentrations.

^bIncludes 40 g of solids added after replacement of HRT-CPP circulating pump.

^cTitanium sample holder inserted prior to run 17-4.

(a)

(b)

Fig. 5.1. HRT Chemical Processing Plant. (a) As initially operated; (b) revised installation. A consistent set of equilibrium conditions is: total volume 140 gal; average solids circulation time 0.5 hr; solids production rate 4 g/hr; collection rate 0.66 g/hr, 16% of total, in (a), 2.4 g/hr, 60% of total, in (b). The direction of core flow may be reversed without affecting the calculated results.

UNCLASSIFIED
ORNL-LR-DWG 18863

Fig. 5.2. Integrally flanged hydroclone.

Typical results with relatively concentrated ThO_2 slurries can be presented graphically as loop concentrations vs time and apparent hydroclone efficiencies vs time. The apparent efficiency is the fraction of the ThO_2 removed while passing through the hydroclone and may be calculated as follows:

$$-VdC_f = C_f ERdt \quad (23a)$$

$$R = \frac{C_f - C_o}{C_f} = \frac{V}{FC_f} \left(\frac{dC_f}{dt} \right) \quad (23b)$$

For a given system the apparent efficiency is proportional to the slope of the concentration vs time curve.

The apparent efficiency (or the concentration vs time) curves have three characteristic concentration ranges (Figures 5.3 and 5.4). For high feed slurry concentrations the apparent efficiency is limited by the concentration which the induced underflow stream can attain, i.e., by the rate at which the slurry can be transferred into the underflow receiver. The value of the apparent efficiency should approach the induced underflow ratio as the concentration increases:

$$\lim R = \left(\frac{B}{F} \right) C_f \rightarrow C_{sb} \quad (24)$$

This induced underflow ratio will tend to be much higher than that measured as C_f approaches 0 since the density gradients will tend to increase the underflow ratio.

The apparent efficiency will have a maximum at some intermediate feed concentration. If settling in the induced underflow receiver results in negligible recycle of slurry to the hydroclone, the apparent efficiency maximum will approximate the value of E_o or E_1 . The decreasing apparent efficiency for low concentrations is due to recycle of slurry from the underflow receiver and/or a true efficiency decrease due to preferential removal of large slurry particles, leaving only the smaller, more difficult to remove material (Figure 5.5). The location of the apparent efficiency maximum will vary depending on conditions, including the starting slurry concentration, the relative loop and underflow receiver volumes, the slurry size distribution, and the value of E_o .

Baffles in the induced underflow receiver may be used to change the performance of a hydroclone--underflow receiver combination. Baffles tend to promote settling in the underflow receiver and to reduce the induced underflow rate. Both of these increase the equilibrium concentration factor, but the reduced underflow ratio reduces the initial removal rate starting with a concentrated slurry. An effective baffle is a simple sheet metal cross with its axis on the hydroclone axis and its top edge 1 to 2 hydroclone diameters below the underflow port.

Fig. 5.3. Hydroclone collection of ThO_2 into induced underflow receivers.

Fig. 5.4. Apparent hydroclone efficiencies for collection of ThO_2 into induced underflow receivers.

Fig. 5.5. Size distribution of unremoved ThO_2 . 1600°C calcined ThO_2 ; H_2O at 25°C ; 0.4 in. dia hydroclone; feed $d_{50} = 2.3$ microns.

The apparent efficiency for a concentrated slurry may often be increased by a line from the top of the underflow receiver to the hydroclone overflow sized to pass 4 to 10% of the hydroclone feed flow. The underflow receiver normally is at a pressure intermediate between the feed and overflow. The by-pass has the effect of converting the hydroclone to continuous underflow with the underflow receiver as a settling tank. If the slurry will not settle in the underflow receiver to give a partially clarified by-pass stream, this stream will return the slurry into circulation and nullify the effect of the hydroclone.

In cylindrical hydroclones with induced underflow receivers the efficiency was appreciably lower than in conical hydroclones (Figure 5.4), and the initial removal rate only slightly increased. This type of design might be useful where caking on the walls or occasional oversized particles might make a conventional conical hydroclone undependable. It would avoid interference by oversize slurry particles which can cause lowered efficiencies even though they are too small to plug the hydroclone ports. Apparently a particle about $2/3$ the diameter of the induced underflow port can be suspended by the two flows in opposite directions near the underflow port. There it may reduce the apparent efficiency by greatly reducing the B/F ratio. Reduced apparent efficiencies believed due to this effect were observed during tests with ThO_2 slurries.

6.0 REFERENCES

1. D. A. Dahlstrom, "Cyclone Operating Factors and Capacities on Coal and Refuse Slurries," Trans. Am. Inst. Min. Eng., 184: 331-44 (1949).
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: 254-72 (1953).
4. D. E. Matschke and D. A. Dahlstrom, "Miniature Hydrocyclones - Energy Requirements and Solids Elimination Efficiency," Chem. Eng. Prog., Part I, 54: 60-4 (1958); Part II, 55: 79-82 (1959).
5. N. Yoshioka and Y. Hotta, "Liquid Cyclones as a Hydraulic Classifier," Chem. Eng., Japan, 19: 632-40 (1955).
6. P. A. Haas et al., "Midget Hydroclones Remove Micron Particles," Chem. Eng. Prog., 53: 203-7 (1957) (ORNL-2301).
7. "Homogeneous Reactor Project Quarterly Progress Report for Period Ending January 31, 1956," ORNL-2057, pp. 41-59.

8. D. Bradley, "The Efficiency of Hydraulic Cyclones for Homogeneous Aqueous Reactor Fuel Processing," AERE CE/M 227 (August 1958).
9. D. Bradley, "A Contribution to the Theory of the Hydraulic Cyclone and Data on the Performance of Small Diameter Cyclones," AERE CE/R 2016 (October 1956).
10. P. A. Haas, "Aqueous Homogeneous Reactor Fuel Processing - The Behavior of Insoluble Corrosion and Fission Products," ORNL-CF-58-5-33 (May 31, 1958).
11. "Homogeneous Reactor Project Quarterly Progress Report for Period Ending October 31, 1958," ORNL-2654, pp. 14-18 (Feb. 9, 1959).
12. "Homogeneous Reactor Project Quarterly Progress Report for Period Ending January 31, 1959," ORNL-2696, pp. 12-17 (April 2, 1959).
13. "Homogeneous Reactor Project Quarterly Progress Report for Period Ending April 30, 1955," ORNL-1895, pp. 176-82 (July 6, 1955).

7.0 APPENDIX

7.1 Derivations of Induced Underflow Equations¹³

Equations for the performance of a hydroclone on an induced underflow receiver can be obtained from algebraic rearrangements of material balances. The induced underflow receiver is assumed agitated to give a uniform concentration throughout. The equations are derived so that they are applicable either to a two-phase system with concentration by the centrifugal field or to a one-phase system with a soluble salt. The hydroclone and its induced underflow receiver are a constant-volume system with equal feed, F, and overflow, O, volumes.

To check the consistency of the volume flows of Fig. 3.1 identities can be written for the flows to and from the whole hydroclone and underflow receiver, the induced underflow receiver, and the hydroclone body at the dotted line.

Material balances can be written for the amount of the second phase or soluble salt for the whole hydroclone-underflow receiver unit or portions thereof. For the whole hydroclone:

$$\begin{aligned}
 FC_f d\theta &= (B + B_r)C_p d\theta \\
 &= (B + B_r) \left(\frac{BC_b + B_r C_p}{B + B_r} \right) d\theta + FC_o d\theta \quad (1a)
 \end{aligned}$$

$$FC_f + BC_p = BC_b + FC_o \quad (1b)$$

For the induced underflow receiver:

$$dS = \frac{(B + B_r)(BC_b + B_r C_p) d\theta}{B + B_r} - (B + B_r) C_p d\theta \quad (25a)$$

$$\frac{dS}{d\theta} = BC_b - BC_p = B(C_b - C_p) \quad (25b)$$

For the hydroclone and underflow receiver:

$$dS = FC_f d\theta - FC_o d\theta \quad (\text{Eq. 2a})$$

$$\frac{dS}{d\theta} = F(C_f - C_o) \quad (\text{Eq. 2b})$$

Material balances written for the overflow and underflow streams respectively are:

$$FC_o d\theta = FC_f(1 - E_1) d\theta + BC_p(1 - E_2) d\theta \quad (\text{Eq. 6a})$$

$$(B + B_r) \left(\frac{BC_b + B_r C_p}{B + B_r} \right) d\theta = B_r C_p d\theta + FC_f E_1 d\theta + BC_p E_2 d\theta \quad (\text{Eq. 3a})$$

$$BC_b = FC_f E_1 + BC_p E_2 \quad (\text{Eq. 3b})$$

Equation 6 is a mathematical definition of E_2 ; i.e., E_2 is the constant which makes Eq. 6 an identity. When either C_p or B is zero, solving Eq. 6 for E_1 gives the expression which normally defines E_o for continuous underflow operation:

$$E_o = (E_1)_{B=0} = \frac{C_f - C_o}{C_f} \quad (\text{Eq. 9})$$

Only three of the above five equations are independent since Eq. 2 can be derived from Eq. 1 and 25 while Eq. 3 can be derived from Eq. 1 and 6.

The values of B/F are determined by using a soluble salt to eliminate the effect of the centrifugal field in the hydroclone. Two procedures were used, each starting with the soluble salt in the induced underflow receiver and a salt-free feed stream. Then $C_f = 0$, $E_2 = 0$, $C_b = 0$, and C_{po} is the initial salt concentration in the underflow receiver. For these conditions, either Eq. 1 or 6 can be reduced to:

$$BC_p = FC_o \quad (\text{Eq. 4a})$$

$$\frac{B}{F} = \frac{C_o}{C_p} = \frac{C_{op}}{C_{po}} \quad (\text{Eq. 4b})$$

The pot concentration, C_p , is the concentration at the underflow port and is not easily measured. The initial pot concentration, C_{p0} , can be determined from samples of the solution put into the underflow receiver. Values of C_{p0} cannot be obtained directly, but may be determined by extrapolation of a C_o vs time curve to zero time. This deviation does not require uniformity of or complete mixing in the induced underflow receiver. If complete mixing is assumed, the following expressions apply:

$$S = V_p C_p \quad (26a)$$

$$dS = V_p dC_p \quad (26b)$$

Equation 26b can be combined with Eqs. 4b and 2a, substituting $C_f = 0$ for the soluble salt, to give

$$\frac{-dC_o}{C_o} = \frac{F}{V_p} \left(\frac{B}{F} \right) d\theta \quad (27)$$

Integration from θ_1 to θ_2 and C_{o1} to C_{o2} gives

$$\frac{B}{F} = \frac{V_p}{F(\theta_2 - \theta_1)} \ln \frac{C_{o1}}{C_{o2}} \quad (\text{Eq. 5})$$

Values of B/F may be obtained from the slope of the $\ln C_o$ vs time curve and Eq. 5.

While values of E_1 may be calculated from conventional hydroclone correlations (Sec. 4.1), values of E_2 are difficult to obtain because of the elusive nature of the induced underflow stream. One method is to use a slurry-free feed stream, $C_f = 0$, to a hydroclone with a slurry in the underflow receiver stirred to maintain a uniform concentration. For this situation Eq. 6 reduces to

$$E_2 = 1 - \frac{FC_o}{BC_p} = 1 - \frac{C_o/C_p}{B/F} \quad (\text{Eq. 7})$$

Combining Eqs. 2a, 26b, and 7 gives

$$dS = V_p dC_p = V_p \frac{F dC_o}{B(1 - E_2)} = FC_o d\theta \quad (28)$$

Integrating from θ_1 to θ_2 and C_{o1} to C_{o2} and rearranging gives

$$E_2 = 1 - \frac{V_p}{B(\theta_2 - \theta_1)} \ln \frac{C_{o1}}{C_{o2}} \quad (\text{Eq. 8})$$

Values of E_2 may be obtained with the slurry similarly to values of B/F with the soluble salt from the C_o vs time curves. Equation 7 may be

used with known values of B/F and C_{p0} by extrapolation to obtain C_{∞} . Or the slope of $\ln C_0$ vs time may be used with Eq. 8. Experimentally determined values of the equilibrium concentration factor, CF_{eq} , may be used with Eq. 11 and known values of B/F and E_1 to calculate values of E_2 .

The equilibrium concentration ratio for $C_f = C_0$ can be obtained by noting that $dS = 0$ and $C_p = C_b$. Substituting $C_f = C_0$ in Eq. 6 and solving for $(C_p/C_f)_{eq}$ gives

$$CF_{eq} = \left(\frac{C_p}{C_f} \right)_{eq} = \frac{F}{B} \frac{E_1}{1 - E_2} \quad (\text{Eq. 11})$$

This equation is an important measure of the performance of an induced underflow system and can be evaluated directly or can be calculated from values of F/B , E_1 , and E_2 .

Rearrangement of Eq. 6 gives

$$\frac{C_0}{C_f} = (1 - E_1) + \frac{BC_p}{FC_f}(1 - E_2) \quad (29)$$

Rearranging and substituting from Eq. 2b and $dS = V_p dC_p$ for a homogeneous underflow receiver gives

$$\frac{C_0}{C_p} = (1 - E_1) \frac{C_f}{C_p} + \frac{B}{F}(1 - E_2) = \frac{C_f}{C_p} - \frac{V_p}{FC_p} \left(\frac{dC_p}{d\theta} \right) \quad (30)$$

Integration from $\theta = 0$ to θ and from $C_p = 0$ to C_p gives

$$C_p = \left(\frac{E_1}{1 - E_2} \frac{C_f F}{B} \right) \left\{ 1 - \exp \left[- \frac{B}{V_p} (1 - E_2) \theta \right] \right\} \quad (\text{Eq. 12})$$

As $\theta \rightarrow \infty$ this equation reduced to Eq. 11. Differentiating with respect to time gives:

$$\frac{dC_p}{d\theta} = \frac{E_1 C_f F}{V_p} \exp \left[- \frac{B}{V_p} (1 - E_2) \theta \right] \quad (\text{Eq. 13})$$

7.2 Experimental Data for Underflow Ratio Determinations

The values considered for obtaining an induced underflow ratio correlation were obtained partly during development studies for this type of hydroclone operation and partly during routine tests of hydroclones after fabrication. Consistent conditions of C_{p0} , ΔP , and temperature were not maintained for all the results reported (Table 7.2). These unrecorded variations may cause part of the scatter shown in Figure 7.1. Also, dimensions were not measured exactly; 0.005- to 0.010-in. variations in D_u for

Table 7.1 Experimentally Observed Induced Underflow Ratios

H₂O at room temperature

LiCl in induced underflow receiver with 500 to 30,000 ppm Li

D _c , in.	L _t , in.	D _u , in.	B/F, ^a %	(B/F) L ³ D _u ^{1.8}
0.16	0.96	0.046	0.37	0.83
			0.51	1.14
		0.051	0.70	1.29
0.25	1.30	0.100	2.50 ^b	3.4
			0.88	3.6
	1.50	0.070	1.40	5.7
			0.90	3.7
			1.36 ^b	5.5
		0.071	1.26 ^b	5.0
			1.32 ^b	5.2
	1.75	0.070	0.79	5.1
			0.75 ^b	4.8
	2.01	0.100	1.14 ^b	5.8
	4.01 ^c	0.100	0.38 ^b	15.3 ^c
	0.40	2.00	0.143	5.26, ^a 5.30
			5.60	14.9
		0.400 ^c	5.0	2.1
2.40		0.100	1.36	11.8
			1.23	11.7
			1.21	11.6
			1.13	9.9
			1.40	12.2
			1.53	13.3
			1.16	10.1
			1.64	14.3
		1.28	11.1	
2.65		0.100	1.00	11.6
2.75		0.400 ^c	3.18	3.4 ^c

Table 7.1 (Continued)

D _c , in.	L _t , in.	D _u , in.	B/F, ^a %	(B/F) L ³ D _u ^{1.8}	
0.40	3.14	0.100	0.57 ^b	11.0	
			0.62 ^b	12.0	
			0.64	12.4	
			0.55	10.7	
	4.00	0.400 ^c	2.72	9.1 ^c	
	4.75	0.400 ^c	1.40	7.8 ^c	
0.50	3.00	0.125	2.03, 1.97	23.0, 22.3	
			1.60	18.1	
			1.80	20.4	
			1.55	17.6	
	3.60	0.050	2.06, ^d 1.93 ^d	23.4, 21.8	
			0.21, ^d 0.21	21.6, 21.6	
0.56	3.20	0.148	2.10	29.0	
0.60	3.60	0.125	1.60	31.4	
			1.51	29.6	
0.80	4.70	0.200	2.52, 2.47	47, 46	
			3.38, ^d 3.10	63, 58	
3.50	21.00	0.875	4.3, ^{d,e} 4.5 ^{d,e}	510, ^e 530 ^e	
			5.1, ^{d,e} 5.3 ^{d,e}	600, ^e 620 ^e	
			4.1, ^{d,e} 4.5 ^{d,e}	480, ^e 530 ^e	

^aTwo values indicate duplicate results for a single hydroclone.

^bThese values are 0.6 of values obtained by use of Eq. 5 as described in Sec. 4.2.

^cBeyond range of empirical equation.

^dCorrected for pressure variation by use of $B/F \propto (\Delta P)^{0.25}$.

^eThese values for a baffled underflow receiver.

Fig. 7.1. The effect of D_c on hydroclone B/F ratios.

the smaller sizes would have resulted in 10% variations in B/F. Results for more carefully measured and controlled conditions (Table 7.2) were the basis for generalizations on the effects of density differences and ΔP variations, and to confirm the $B/F = f(D_u, D_c, L_t)$ correlation.

Results typical of the two procedures for measuring B/F ratios are shown by concentration vs time curves (Figures 7.2 and 7.3). The B/F ratios are calculated as shown on Figure 7.2 by use of Eq. 4. For Figure 7.3, the ratio is calculated from Eq. 5 as follows:

$$\frac{B}{F} = \frac{V_p}{F} \left(\frac{1}{\theta_2 - \theta_1} \right) \ln \frac{C_{o1}}{C_{o2}}$$

$$\frac{B}{F} = \left[\frac{1}{400} - \frac{1}{200} \right] \ln \frac{25}{0.7} = \frac{3.58}{400}$$

$$\frac{B}{F} = 0.009 = 0.9\%$$

The B/F value from Eq. 4 would be about 0.6 of this value or 0.55%. The values for varying underflow receiver lithium concentrations (Table 7.2) were intended to determine the effects of density differences at the underflow port since the high LiCl concentrations would give solutions with greater densities than those of water. The results for varying hydroclone-pot orientations (Table 7.3) were also intended to indicate density effects. The increased density for $C_p = 15,000$ ppm of lithium as compared to $C_p = 3000$ ppm appeared to decrease the B/F ratio as determined from Eq. 4; however, the effects were small and of the order of experimental variations. A pronounced density effect was observed for B/F determinations by use of Eq. 5; this could be partly due to less effective mixing as the density differences increased.

Fig. 7.2. Determination of induced underflow ratio from initial concentrations.

Fig. 7.3. Determination of an underflow ratio from the overflow stream concentration vs. time.

Table 7.2. Experimentally Observed Induced Underflow Ratios for Controlled Conditions

$C_f = 0$; H_2O at room temperature

D_u measured; other dimensions as on construction blueprints

ΔP for feed line, discharge to atmospheric pressure

Values of B/F from Eq. 4 as described in Sec. 4.2

Hydroclone Dimensions

Diameter, D_c , in.	0.16	0.25	0.40	0.40	0.40	0.50	0.50	0.60	0.80	3.50
Overflow dia, D_o , in.	0.035	0.053	0.080	0.100	0.080	0.100	0.100	0.120	0.160	0.688
Underflow dia, D_u , in.	0.046	0.070	0.100	0.100	0.143	0.050	0.125	0.125	0.213	0.875
Length, L, in.	0.96	1.50	2.40	3.14	2.00	3.60	3.00	3.60	4.70	21.0

B/F values for values of:

<u>C_p, ppm Li</u>	<u>ΔP, ft</u>										
750	28	-	-	-	-	-	-	-	-	-	3.15, ^a 3.24 ^a
	100	-	-	-	-	-	-	1.60	-	-	-
3,000	16 to 30	-	-	-	-	-	-	-	-	-	3.22, ^a 3.98 ^a
	45	-	-	-	-	4.31	0.17	1.69	-	2.78	3.36, ^a 3.68 ^a
	100	0.37	0.88	1.28	0.55, 0.64	5.30	0.21	2.03, 1.97	1.60	3.10	-
	180	-	-	-	-	-	-	2.22	-	-	-
15,000	100	0.51	-	-	-	-	-	1.80	1.51	-	-
6,000 to 20,000 ^b	100	-	1.38	1.27, 1.36	-	5.60	-	1.55	-	2.47, 2.52	-
30,000 ^b	100	0.70 ^c	0.9, 1.36	1.40	-	-	-	-	-	-	-

^aValues for a baffled underflow receiver.

^bThese values are comparable to those for 750, 3000, and 15,000 ppm lithium but were run earlier, some with hydroclone units of different D_o than those listed.

^c $D_u = 0.051$.

Table 7.3 Experimentally Observed Efficiencies and Underflow Ratios for Several Hydroclone—Underflow Receiver Orientations

A. Hydroclone: $D_c = 0.50$, $D_u = 0.125$, $L_t = 3.00$, $\Delta P = 100$ ft

Material: LiCl

<u>Orientation</u>	<u>C_p, ppm Li</u>	<u>B/F</u>
Normal-vertical	2,950	2.03
Normal vertical	3,150	1.97
Inverted vertical	3,150	1.90
On side-horizontal	3,150	1.93

B. Hydroclone: $D_c = 0.25$, $D_u = 0.070$, $L = 1.50$ or, $\Delta P = 100$ ft

or $D_c = 0.40$, $D_u = 0.100$, $L = 2.40$, $\Delta P = 100$ ft

Material: synthetic corrosion products

<u>Orientation</u>	<u>Hydroclone Diameter, in.</u>	<u>Efficiencies (E_o), %</u>
Upright	$D_c = 0.25$	14.1, 15.5, 13.5, 20.0
Upright	$D_c = 0.40$	17.9, 15.7, 14.3, 14.0, 13.0
Inverted	$D_c = 0.25$	15.5, 13.6
Inverted	$D_c = 0.40$	9.7, 12.3

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

ORNL-2876
UC-4 Chemistry-General
TID-4500 (15th ed.)

INTERNAL DISTRIBUTION

1. C. E. Center	62. R. E. Blanco
2. Biology Library	63. G. E. Boyd
3. Health Physics Library	64. W. E. Unger
4-5. Central Research Library	65. A. T. Gresky
6. Reactor Experimental Engineering Library	66. E. D. Arnold
7. HRP Director's Office	67. C. E. Guthrie
8-27. Laboratory Records Department	68. J. W. Ullmann
28. Laboratory Records, ORNL R.C.	69. K. B. Brown
29. A. M. Weinberg	70. K. O. Johnsson
30. L. B. Emlet (K-25)	71. J. C. Bresee
31. J. P. Murray (Y-12)	72. P. M. Reyling
32. J. A. Swartout	73. R. G. Wymer
33. E. H. Taylor	74. S. E. Beall
34. E. D. Shipley	75. E. G. Bohlman
35-36. F. L. Culler	76. W. D. Burch
37. M. L. Nelson	77. S. D. Clinton
38. W. H. Jordan	78. J. R. Engel
39. C. P. Keim	79. R. S. Greely
40. J. H. Frye, Jr.	80-99. P. A. Haas
41. S. C. Lind	100. E. Lamb
42. A. H. Snell	101. J. T. Long
43. A. Hollaender	102. R. N. Lyon
44. K. Z. Morgan	103. J. P. McBride
45. M. T. Kelley	104. R. A. McNees
46. T. A. Lincoln	105. C. F. Parsly, Jr.
47. R. S. Livingston	106. S. A. Reed
48. A. S. Householder	107. W. F. Schaffer
49. C. S. Harrill	108. J. W. Snider
50. C. E. Winters	109. D. G. Thomas
51. H. E. Seagren	110. C. D. Watson
52. D. Phillips	111. M. E. Whatley
53. W. K. Eister	112. E. L. Youngblood
54. F. R. Bruce	113. D. L. Katz (consultant)
55. D. E. Ferguson	114. I. Perlman (consultant)
56. R. B. Lindauer	115. M. Benedict (consultant)
57. H. E. Goeller	116. C. E. Larson (consultant)
58. C. W. Hancher	117. H. Worthington (consultant)
59. R. A. Charpie	118. J. H. Rushton (consultant)
60. J. A. Lane	119. ORNL - Y-12 Technical Library, Document Reference Section
61. M. J. Skinner	

EXTERNAL DISTRIBUTION

120. F. C. Moesel, Atomic Energy Commission, Washington
121. Division of Research and Development, AEC, ORO
122-678. Given distribution as shown in TID-4500 (15th ed.) under Chemistry-General category (75 copies - OTS)