Prediction of Cake-washing Results with Continuous Filtration Equipment

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This paper proposes a theory of filter-cake washing on continuous filtration equipment based upon the assumption that mixing of the strong liquor and wash fluid is controlling. The theory can be conveniently applied to experimental filtration leaf tests for determining wash efficiency and is easily extrapolated to full-scale results with the normally experienced uneven cake thickness and wash-fluid distribution taken into account.

To obtain the necessary wash-fluid volume for proper soluble removal, a correlation method of wash time as a function of wash ratio with parameters of cake-formation time has been derived from commonly accepted filtration theory. Experimental and plant data indicate a close agreement with the theory, and the method can be employed to predict filtration rate as a function of wash ratio. A typical illustration has been given to determine filtration requirements for recovering soluble uranium after leaching of the ore by continuous filtration. Washing rate was proved to be controlling, and this design based only on cake-formation rate would yield insufficient wash ratios and excessive soluble uranium loss. Final filter and flow-sheet design must be based on uranium recovery which can be predicted by the proposed methods.

In any continuous filtration application, at least two distinct rates must always be considered and in many cases even three or four. These may be briefly summarized as (1) cake-formation rate, (2) cake-"dewatering" rate, (3) cake-washing rate to remove soluble values or contaminations, (4) thermal drying rate of the filter cake. The first two rates are always encountered, but the third and fourth depend on the application. Generally speaking, one of the four rates will be controlling in the determination of filtration requirements, as it will exhibit the most critical influence. Careful investigation of each rate encountered in a filter application must be made prior to the full-scale application. It is also emphasized that each rate is controlled by diverse factors or influenced to a different degree by similar variables; therefore, analysis methods must be developed for each phase of filtration which allow determination of individual requirements that can later be incorporated into prediction of the following important results or specifications over the desired range of operating conditions: (1) filtration rates, (2) final cake moisture or liquor content, (3) filtrate clarity, (4) final cake soluble concentration or recovery of soluble values, (5) wash-fluid requirements, (6) thermal requirements when cake drying is practiced, (7) power and capacity requirements for all auxiliaries such as filtrate and vacuum pumps, and (8) required filter design to achieve all objectives.

The following discussion will be limited to determination of cake-washing results and requirements. However, this can never be dissociated from the other phenomena and the methods to be developed will also illustrate how cake-washing requirements can be designed to predict all the necessary results and specifications. Other papers have dealt with the other three phenomena and can be referred to for greater detail (*2, 5, 6, 7*).

THEORY OF CAKE WASHING

The theory of filter cake washing must be considered from two standpoints: (1) removal or displacement of cake liquor by the washing fluid and (2) wash-fluid rate through the filter cake. The former is naturally important in determining total strong liquor or soluble value recovery from the feed slurry; however, wash rate must also be known in order that the proper amount of wash fluid may be administered.

Removal of Cake Liquor By Washing

The effectiveness of removal of liquor or soluble salts by cake washing has been the subject of different and extensive theories. However, they have either been concerned largely with batch filtration utilizing relatively thick cakes and single-phase flow or the migration of fluids within porous media found in oil field reservoirs. This is in contrast to washing of cakes in continuous filtration, where two-phase flow may occur and thin cakes with relatively large wash-fluid rates are involved.

Taylor (*9*) analyzed capillary flow and von Rosenberg (*10*) extended the qualitative concept of displacement in a single pore to more complex porous media with numerous pores. The penetration of resident fluid by invading fluid establishes a radial concentration gradient, and consequently the fluid interdiffuses. Ruth, on the other hand, proposed displacement of one fluid by another in both laminar and nonlaminar flow (*4*). Presumably it was felt that the rapidity of washing precluded any significant amount of interdiffusion between the two fluids.

From the available experimental data, it was felt by the authors that mixing within the cake would probably be the controlling factor in removal of strong liquor by washing on a continuous filter. This would be analogous to the so-called "diffusion" washing equation postulated by Rhodes as follows (*3*):

$$\frac{c}{c_0} = e^{-kFt/L} \tag{1}$$

In order to apply this type of equation to continuous-filtration cake washing, it is convenient to develop the expression on the basis of percentage of solute remaining in the filter cake, with 100% being that remaining if no washing were performed. Accordingly, Equation (1) was revised as follows:

By material balance,

$$S_w = (1 - R)S_0 \tag{2}$$

Thus,

$$\frac{dS_w}{dV_w} = c = -S_0 \frac{dR}{dV_w} \tag{3}$$

Also,

$$c_0 = \frac{S_0}{V_l} \tag{4}$$

Therefore,

$$\frac{c}{c_0} = -\frac{S_0\, dR/dV_w}{S_0/V_l} = e^{-kFt/L} = e^{-kV_w/L} \tag{5}$$

Before integrating Equation (5), one can substitute an equivalent for cake thickness L,

$$V_l = \frac{L\rho_c X}{\rho_l} \quad \text{or} \quad L = \frac{\rho_l V_l}{\rho_c X} \tag{6}$$

It should be noted that a unit filtration area is assumed for Equation (6). Substituting for L in Equation (5) gives

$$\frac{dR}{dV_w} = -\frac{1}{V_l} \exp\left[\frac{-k\rho_c X V_w}{\rho_l V_l}\right] \tag{7}$$

Equation (7) may now be integrated for a constant V_l condition (i.e., constant cake thickness, which also stipulates constant V_l, ρ_c, ρ_l, X, and k). In addition, the term $k\rho_c X/\rho_l$ can be combined into a single constant k'.

Thus,

$$R = \frac{1}{k'} e^{-k' V_w / V_l}$$

$$+ \text{ integration constant} \qquad (8)$$

Boundary conditions implied by Rhodes's original equation are $R = 0$ at $v_w =$ infinity. If these are employed, the integration constant becomes zero. Thus, taking the log of both sides of Equation (8) gives

$$\log R = -k' \frac{V_w}{V_l} + \log (1/k') \qquad (9)$$

Equation (9) indicates that a semilog plot of log R vs. V_w/V_l should yield a straight-line relationship. The term V_w/V_l is the number of displacements of wash (i.e., wash volume divided by original liquor volume in the cake prior to wash) and is termed the "wash ratio n."

To prove the relationship between R and wash ratio n, extensive data on several different applications were compiled. Figure 1 is a typical plot for the washing of aluminum trihydrate with water. It is crystalized from a caustic and carbonate liquor, and the filter cake must be washed to recover practically all Na_2O values.

Observation of Figure 1 indicates a good straight-line agreement with the data below wash ratios of 2.1. Results on other materials yielded straight-line relationships. Deviations beyond a wash ratio of 2.0 have generally been well below the extrapolated straight line. However, care should be exercised in employment of Equation (10) above n values of 2.0 without proper experimental work. It should also be noted that where cake-washing rate and removal of solubles are controlling, it will usually be more economical to install two stages of filtration with n values below 2.0 to obtain desired results rather than to employ a single state with a high wash ratio.

The equation of the average straight line of plots similar to Figure 1 is

$$\frac{R'}{100} = \left(1 - \frac{E}{100}\right)^n \qquad (10)$$

Thus, if the wash efficiency E is established, Equation (10) may be employed to determine the recovery of soluble values as a function of applied wash ratio. If filtration leaf-testing techniques are employed to obtain a plot similar to Figure 1 and thus determine E, the wash efficiency should be lowered to take into account full-scale deviations, which are caused by uneven cake thicknesses across the filtration area and uneven wash-water distribution across the cake. Normally, experimental wash efficiency E will be lowered by 10% but the actual value will depend on the type of filter and the method of applying the wash fluid.

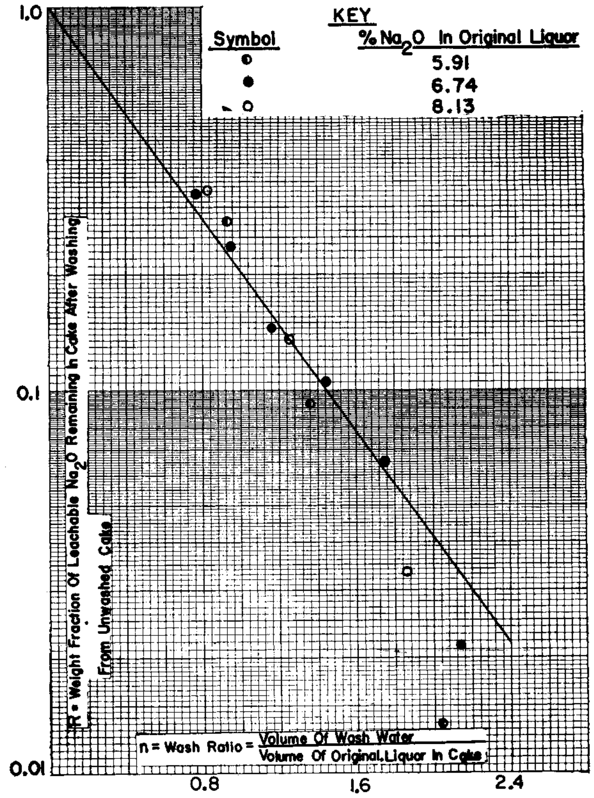

Fig. 1. Weight fraction leachable Na_2O remaining in filter cake after washing from original unwashed cake, R, vs. wash ratio, n.

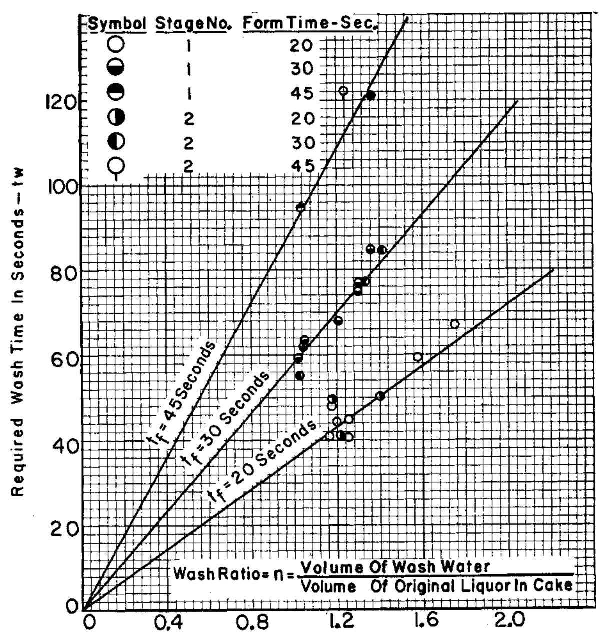

Fig. 2. Wash time as a function of wash ratio parameters of form time. First- and second-stage acid-leached uranium-ore filters. Cotton ST-19 filter media, 23 in. Hg vacuum; 0.1 sq. ft. leaf, pH-1.975 to 1.99; average percentage of −200 mesh in filter cake, 55.1 wt. %; feed percentage of solids, stage 1—58.4%, stage 2—60.0%.

In order to calculate the recovery of soluble values from the original feed liquor per filter station, the following data are necessary: (1) feed solids concentration, (2) filter cake liquor content prior to washing, (3) liquid content of cake at discharge from the filter, and (4) wash efficiency E determined by experiment and properly corrected for full-scale application. It is readily apparent that all these four points can be determined by proper filtration leaf testing. The first recovery is obtained by simple material balance around the cake-formation and initial "dewatering" phase of the filter cycle prior to cake washing. The remaining recovery is calculated by use of Equation (10).

Wash efficiency E values have been

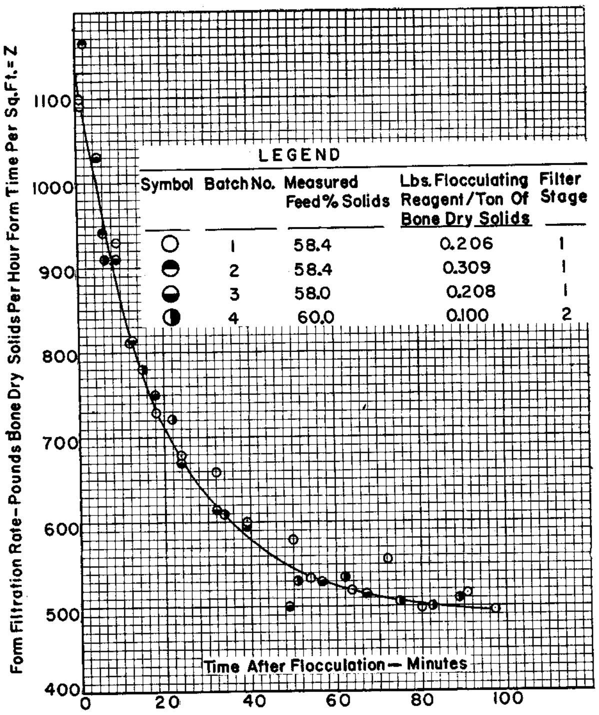

Fig. 3. Leaf-test form filtration rate vs. time after flocculation. Leached uranium ore slurries. Cotton ST-19 filter media; 23 in. Hg vacuum; average %-200 mesh in filter cakes-55.1 wt. %; *p*H − 1.975 to 1.99—filtration stages 1 and 2 included; form filtration rates corrected to 30 sec. form time.

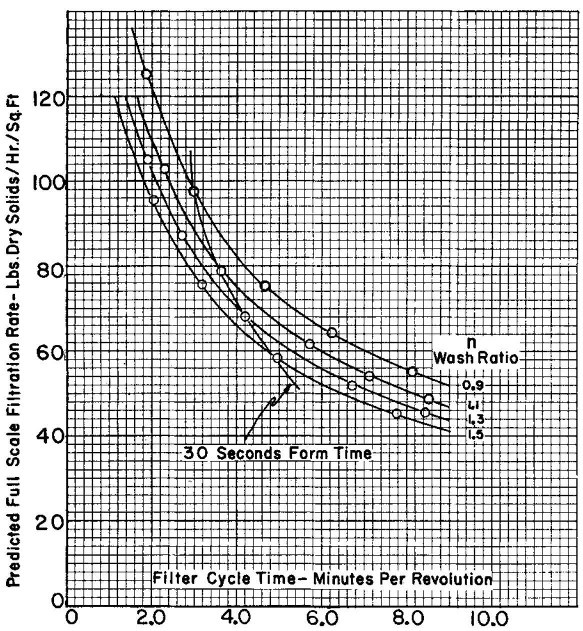

Fig. 4. Predicted full-scale filtration vs. cycle time. Parameters of wash ratio—leached uranium slurry. Basis: 20-min. retention time after flocculation; drum filters—cotton St.-19F; filter media—23 in. Hg vacuum; 60% feed solid concentration, 80% design factor on leaf-test data.

found to vary from a minimum of 35% to a maximum of 86%. Generally speaking, the lower values are found with cakes that wash very rapidly such as some long fibers employed in paper making. This is probably due to chaneling and insufficient time for more complete mixing. It should also be noted that cake moisture content after washing and final "dewatering" is usually lower than before washing. This phenomenon has been found to be more pronounced as the viscosity difference between original liquor and wash fluid increases. This naturally increases the efficiency of washing due to improved drainage.

RATE OF CAKE WASHING

From the preceding, it has been proposed that recovery of soluble values from a filter cake by cake washing will be a function of wash ratio n. Once this function has been determined, it becomes possible to calculate both the final product purity and total recovery of soluble material per filter stage for any value of applied wash. However, time required for washing must also be related to wash ratio and other filtration factors in order to predict full-scale filtration rates which permit the realization of desired soluble recoveries. The modified Hagen-Poiseuille equation for flow of liquor through capillaries generally applied to filtrate rate studies is (*1*)

$$\frac{dV}{Adt} = \frac{(-\Delta P)}{\mu\left(\alpha w \dfrac{V}{A} + r\right)} \qquad (11)$$

As continuous filtration is a cyclic process, the actual filtration rate experienced from each square foot of area per unit time must be obtained from the integrated form of Equation (11). Before this integration is performed however, it is convenient to discuss the term r, which is the resistance of the filter media; drainage decking; and internal piping of the filter. It is apparent that correct filter design can result in a negligible resistance for the drainage decking and internal piping and will be assumed so in this paper. This may not necessarily be true for filter media if selection is improper or an extremely "tight" medium is employed. However, as cake-formation time in continuous filtration with cake washing is usually achieved in a range from a few seconds to a maximum of two minutes, it would be expected that filter-media resistance would be small to negligible. While the resistance r will be assumed negligible, correlation methods will be given to prove this assumption in the course of the theoretical development.

With r assumed negligible, Equation (11) can be integrated between the limits of $V = 0$ and V_f with $t = 0$ and t_f. The integration assumes parameters of constant pressure drop, feed-solids concentration, temperature, and specific cake resistance. Thus

$$\frac{V_f}{A} = \left[\frac{2(-\Delta P)t_f}{\mu\alpha w}\right]^{1/2} \qquad (12)$$

With t_f expressed in minutes, multiplying both sides of Equation (12) by $60/t_f$ would yield filtration rate as volume of filtrate per unit area per hour of cake-formation time. Thus no consideration at this point is given to time required for cake washing, dewatering, or discharge. However, this can be easily achieved once the fraction of the total filter-cycle time available for cake formation is known; therefore

$$\frac{60}{t_f}\cdot\frac{V}{A} = Z = \left[\frac{7{,}200(-\Delta P)}{\mu\alpha w t_f}\right]^{1/2} \qquad (13)$$

Z is termed the "form filtration rate" and can be expressed in terms of weight of dry cake solids per unit area per hour of cake-formation time by multiplying both sides of Equation (13) by w.

From Equation (13), a log-log plot of Z as a function of cake-formation time t_f should yield a straight line of slope -0.50 for constant-feed-solids concentration, size distribution, and pressure drop. If a straight-line relationship is not experienced, this would indicate that the filter-media resistance r could not be neglected. For most continuous-filtration problems, the straight-line correlation has resulted with proper filter-media selection. In several cases slopes will be more negative than -0.50 but this can be traced to migration of fines within the filter cake with time causing a change in permeability.

While Equation (13) is convenient for determining cake-formation filtration rates, it cannot serve to predict cake-washing times. If the wash fluid is assumed equal to the viscosity of the feed liquor, the wash rate per unit area from Equation (11) with $r = 0$ should be equal to

$$\text{wash rate} = \left(\frac{dV}{A\,dt}\right)_w = \frac{(-\Delta P)}{\mu \alpha w \dfrac{V_f}{A}} \quad (14)$$

As no solids are being deposited during washing, the wash rate should remain constant. Furthermore, if viscosities for both the wash and feed liquor are known, reasonable estimation of wash rate could be obtained by multiplication of Equation (14) by the ratio of the reciprocal of viscosities. From Equation (14) total wash volume after substituting for V_f/A from Equation (12) is

$$\frac{V_w}{A} = t_w\left(\frac{dV}{A\,dt}\right)_w = \frac{(-\Delta P)t_w}{\mu \alpha w \dfrac{V_f}{A}}$$

$$= \left[\frac{(-\Delta P)}{2\mu \alpha w t_f}\right]^{1/2} t_w \quad (15)$$

Equation (15) can be converted to a wash-ratio expression by dividing by the volume of liquor in the cake prior to washing. Volume of cake liquor prior to washing can be expressed by revising Equation (12) to the following:

$$\frac{V_l}{A} = K\left[\frac{2(-\Delta P)t_f}{\mu \alpha w}\right]^{1/2} \quad (16)$$

Dividing Equation (15) by V_l/A or its equivalent and rearranging gives

$$t_w = 2Kt_f\frac{V_w}{V_l} = 2Kt_f n \quad (17)$$

From Equation (17) a plot of required wash time t_w as a function of wash ratio n should yield straight lines going through the origin with parameters of cake formation times t_f. Furthermore, at the same wash ratio, required wash times should be theoretically directly proportional to cake-formation times. It is stressed that such plots assume constant filter feed-solids concentration and size distribution, pressure drop and cake-liquor content prior to washing for any particular filtration problem. If these values are varied appreciably, additional parameters would be nesessary.

A typical plot of required wash time as a function of wash ratio is illustrated by Figure 2. The tests were performed on filtration and washing of acid-leached uranium ore slurries of constant feed solids concentration, size distribution, and pressure drop. It will be noted that a reasonable straight-line agreement is

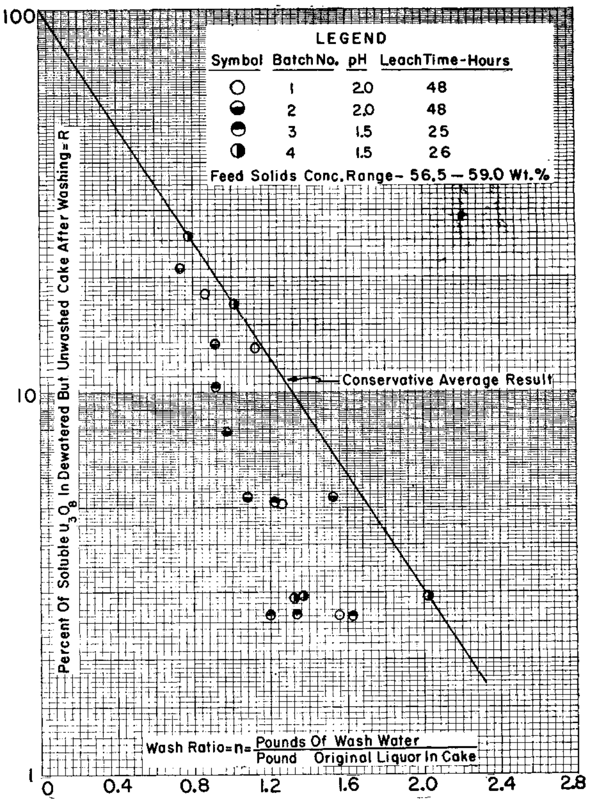

Fig. 5. Percentage of soluble uranium in dewatered but unwashed cake after washing vs. wash ratio.

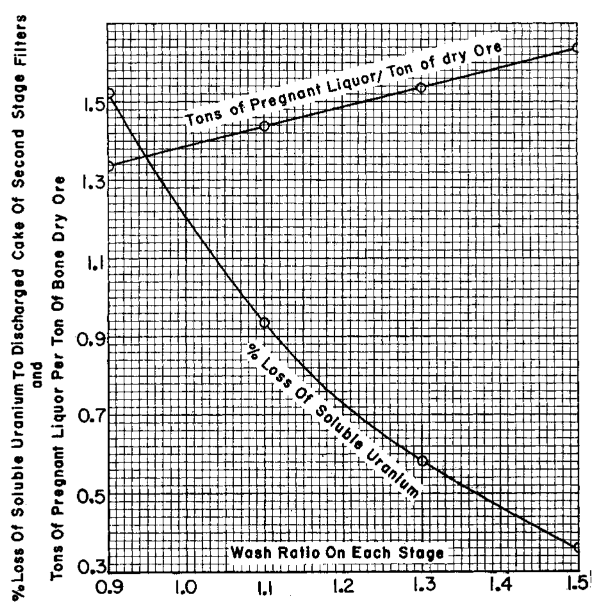

Fig. 6. Predicted % loss of soluble uranium to discharged second-stage filter cake and tons of pregnant liquor per ton of dry ore vs. wash ratio per filter stage. Bases: feed solids concentration to stages I and II = 60.0 wt. %; cake moisture content prior to washing, stage I—19.7%; cake moisture content prior to washing, stage II—19.35%; cake washing efficiency E — 70%; cake moisture content at discharge, stage I—18.0%; cake moisture content at discharge, stage II—17.5%; two-stage drum filtration and cake washing.

obtained for all parameters. Furthermore, the ratio between parameters at the same wash ratio is only slightly greater than the ratio of cake-formation times. This small increase over the theoretical ratio is due to the slightly greater cake-liquor contents prior to washing that were experienced in this case as cake-formation time was increased.

By use of graphs similar to Figure 2 in conjunction with log-log plots of form-filtration rates as a function of cake-formation time, it is possible to predict full-scale filtration rates as a function of wash ratio. Thus, filter design can be matched to obtain desirable soluble recovery or elimination as determined by the required wash ratio on the filter.

PREDICTION OF FULL-SCALE RESULTS AND FILTER-STATION REQUIREMENTS

In order to illustrate the application of the preceding development, a typical case will be analyzed. Although continuous drum filters will be employed in the example, the method may be applied to other types of continuous filters as long as appropriate consideration is given to the allowable time for cake washing for the particular filter construction.

Uranium ore is processed by leaching the finely ground solids in an acid (normally sulfuric acid) or carbonate liquor for 8 to 72 hr. Continuous leach agitators in series are generally used and solids concentrations of 55 to 65 wt. % are employed in order to reduce reagent consumption and holdup volume. After leaching, the "pregnant liquor" containing the uranium in solution must be separated from the very large amount of gangue solids before further processing can be done to finally obtain a dried uranium precipitate of sufficient purity to meet rigid specifications. In addition, the U_3O_8 content in the dry ore may be as low as 0.08 wt. %, which necessitates a soluble uranium recovery of 99.5% in separating the gangue solids from the "pregnant liquor." Finally, liquor volumes after separation normally must be maintained within certain limits in order to minimize capital investment and operating costs in the remainder of the flow sheet.

General practice where filtration is used for recovery of "pregnant liquor" is to employ two-stage continuous-drum filtration with cake washing on each stage and intermediate repulping. By this method, initial investment and operating costs are minimized and the flow sheet is simplified. However, care must be exercised in original design to ensure that a sufficient wash ratio will be experienced on each filter stage. Accordingly, filtration rates are based upon a design wash ratio that will limit soluble uranium losses to a maximum of 0.5%.

In the particular application to be illustrated, design solids concentration from the leach agitators was 60.0 wt. % with 55 to 57% −200 mesh in the dry solids. Several filtration leaf tests were performed at 58 to 60% solids concentration on many slurries in order to determine form-filtration rates. Because of the nature of the slimes created in both the grind and leach circuits together with the acid content of the liquor, flocculating reagents must be employed to agglomerate these fractions. Jaguar (a refined endosperm of the Guar seed) was found to be optimum for this slurry on the filter application. However, owing to the acid nature of the pregnant liquor, a partial degradation of the flocculi with time was apparent which also affected filtration rate. Accordingly, extensive tests were made to observe the magnitude of the breakdown.

Figure 3 is the resultant plot of form-filtration rate as a function of time after flocculation. Three batches of first-stage feed slurry ranging from 58.0 to 58.4 wt. % solids concentration were tested and one second-stage batch at 60 wt. % solids concentration. Average −200 mesh content of the solids was 55.1 wt. %. It will be noted that all form-filtration rates have been corrected by means of Equation (13), to 30 sec. form time as form times ranging from 20 to 60 sec. were investigated. It was stated earlier that the square-root relationship was appropriate if filter-media resistance was negligible and there was no migration of fines within the cake. The close agreement of the data with the average curve drawn in Figure 3 indicates that these assumptions are correct for the slurries tested.

The average curve of Figure 3 is typical of many leached uranium slurries tested in that flocculi degradation is quite rapid initially but asymptotically approaches a minimum form-filtration rate. It should be emphasized that the minimum value still represents an operable condition but naturally it is desirable to take advantage of higher filterability by designing the filter stations for minimum holdup time. The design basis for this application was 20-min. retention time, which yields a sufficient engineering safety factor. Thus, from Figure 3, form-filtration rate Z at any form time t_f would be

$$Z = 715\left(\frac{0.5}{t_f}\right)^{1/2} \qquad (18)$$

During the leaf tests various aliquots of wash fluid were applied to the filter cakes formed at three different cake-formation and wash times measured. Filter-cake moisture contents after 30 sec. dewatering time both before and after washing were determined so that wash fluid applied in terms of wash ratio might be calculated. Wash ratio was measured as pounds of wash fluid per pound of cake moisture owing to the insignificant difference in specific gravity between the two liquids. Thus a plot of wash time as a function of wash ratio with parameters of cake-formation time was developed and was given earlier in Figure 2. It will be noted that both filtration stages are included in this plot and results were similar.

Employing Equation (18) and Figure 2 makes it possible to determine full-scale filtration rates as a function of wash ratio. In this application 105° of the periphery of the drum filter is employed for cake washing. This design permits proper dewatering prior to and after washing, which is essential to high recoveries. In addition, a design factor of 80% on leaf-test form-filtration rates is utilized in predicting full-scale rates. To illustrate the calculation of full-scale results, the following example is given

To find: Full-scale filtration rates at 0.75 min. form time and 1.5 wash ratio

Wash time at 1.5 wash ratio
= 135.7 sec. = 2.26 min. (from Figure 2)

Cycle time = 2.26 × 360°/105°
= 7.75 min./rev.

Form filtration rate = 715 $(0.5/0.75)^{1/2}$
= 584 lb. dry solids/(sq. ft.)(hr.) form time

Predicted full-scale rate

$$= 584 \times \frac{0.75 \text{ form time}}{7.75 \text{ total time}} \times \begin{matrix}0.8 \text{ design}\\ \text{factor}\end{matrix}$$

= 45.1 lb. dry solids/(sq. ft.)(hr.)

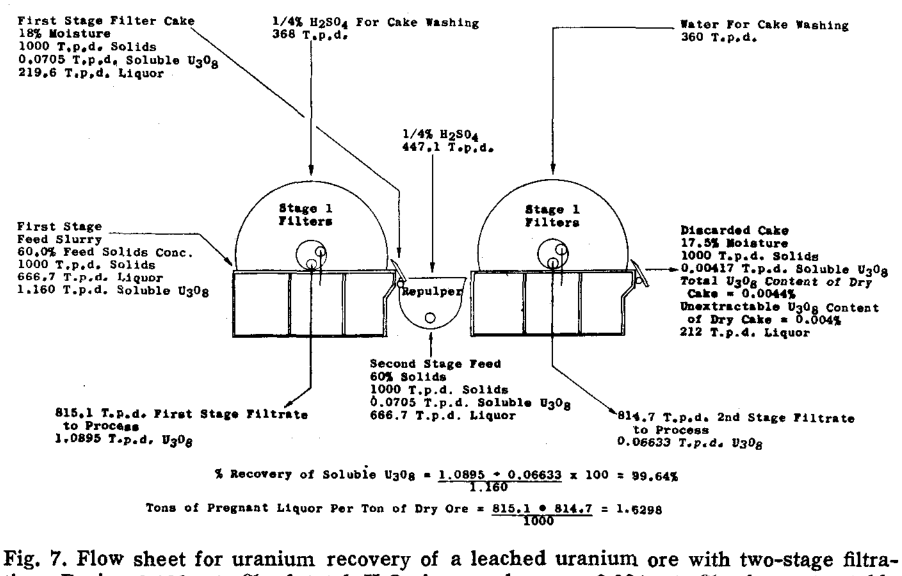

Fig. 7. Flow sheet for uranium recovery of a leached uranium ore with two-stage filtration. Basis: 0.120 wt. % of total U_3O_8 in raw dry ore; 0.004 wt. % of unextractable U_3O_8 in raw dry ore; 1.5 wash ratio on stages I and II—70% washing efficiency = E; 1,000 tons/day of dry ore to plant.

Figure 4 is the resultant plot of predicted full-scale filtration rate as a function of filter-cycle time with parameters of wash ratio (0.9, 1.1, 1.3 and 1.5 lb. of wash fluid/lb. of moisture in the unwashed cake). The curves obtained are typical in that filtration rate increases rapidly as filter-cycle time is reduced. It is apparent that wash ratio is a very important criterion in that an appreciable displacement of the parameter occurs as wash ratio is decreased. Also included on the graph is a parameter of 30 sec. form time. This form time was employed as a design basis as reasonable cake thicknesses of 0.5 in. were obtained. This basis would permit approximately 30% excess capacity to handle peak-tonnage loadings merely by reducing filter-cycle time through the variable-speed drive on the filter. This excess capacity is also obtained without appreciable loss in soluble uranium, as design-wash ratio can be maintained.

To illustrate further the importance of cake-washing rates in determining full-scale filtration rates, it is interesting to note the percentage of cycle time devoted to cake formation. In the sample calculation given above, cake-formation time was 0.75 min. and filter-cycle time equaled 7.75 min./rev. Thus cake-formation time was only 9.7% of total cycle time. If washing was not performed, maximum cake-formation time would be about 35% of the total cycle time for a standard low-submergence filter. It is apparent that the necessary wash ratio for proper uranium recovery could not be experienced if design was based solely on cake-formation time.

To calculate soluble uranium recovery, wash efficiency E for cake washing must be determined. Figure 5 is a semilog plot of percentage of soluble U_3O_8 remaining in the cake after washing, on the basis of 100% remaining if no washing were performed (R'), as a function of wash ratio n. It will be noted that a straight line has been drawn for the data through $R' = 100$ at $n = 0$. This line has been termed a "conservative average" as the majority of data lie to the left of the line. Because of the critical importance of maintaining a very low soluble-uranium loss, the line is not drawn through the average of the data points but instead through the poorest results. Thus average results should be improved over predicted values

From Figure 5, at a wash ratio $n = 1.0$, $R' = 17.5\%$. Thus wash efficiency $E = 100 - R' = 82.5\%$. In determining wash efficiencies of many different leached uranium ores, wash efficiency E values have varied between the narrow range of 80 to 86%. For full-scale predictions wash efficiency E was assumed as 70%. This yields a safety factor of 12.5% to account for uneven cake thickness and wash-water distribution. Thus Equation (10) becomes

$$R' = 100(0.3)^n \qquad (19)$$

It is now possible to calculate full-scale soluble-uranium recovery as a function of wash ratio. The following assumptions, all determined from experimental data, are necessary:

1. Feed-solids concentration to both filter stages = 60.0 wt. %.
2. Moisture content prior to washing

   Stage I = 19.7 wt. %
   Stage II = 19.35 wt. %

3. Moisture content in cake at discharge

   Stage I = 18.0 wt. %
   Stage II = 17.5 wt. %

4. Equation (19) is employed for calculation of soluble-uranium recovery by cake washing.

Figure 6 is a plot of percentage loss of soluble uranium to the discharged cake of the second-stage filters as function of wash ratio. The same wash ratio is applied to both filter stages, which is normal in uranium-ore processing. It will be noted that a wash ratio of at least 1.363 would have to be employed to minimize soluble uranium loss to 0.5%.

Also included in Figure 6 is a plot of tons of pregnant liquor per ton of dry solids. Plant limitations require a maximum design value of 1.65 tons of pregnant liquor per ton of dry solids. Because of the importance of minimum soluble uranium loss, a wash ratio of 1.5 was selected for final design. Thus, from Figure 6, soluble-uranium loss is 0.36% and pregnant liquor rate is 1.63 tons/ton of dry ore.

Figure 7 is the resultant material-balance flow sheet for the two-stage operation. A design rate of 1,000 tons of dry ore/day has been assumed with 0.120 wt. % total U_3O_8 in the raw dry ore and 0.004 wt. % being unextracted by leaching. One-quarter percent sulfuric acid is employed for first-stage cake washing and repulping to maintain proper pH level. Fresh water is used for second-stage cake washing. All other assumptions have been given previously.

Because of the selected design wash ratio of 1.5 to ensure proper soluble-uranium recovery, design filtration rate can also be determined. From Figure 4, at the design cake-formation time of 30 sec. with a 1.5 wash ratio per filter stage, full-scale filtration rate equals 58.5 lb. of dry solids/(hr.)(sq. ft.). Design cycle time would be 4.90 min./rev. Thus, for a plant rate of 1,000 tons of dry ore/day, 1,426 sq. ft. of filtration area/stage would be required.

NOTATION

A = area
c = concentration of the solute in the filtrate at any time after washing begins, weight per unit volume
c_0 = concentration of the solute in original liquor
E = wash efficiency, % = 100 − R' at $n = 1.0$
F = wash flow rate, volume per unit time
k, k', K = constants
L = cake thickness, length
n = wash ratio = volume of wash fluid per unit volume of original liquor in unwashed cake
R = weight fraction of solute remaining in cake after washing on the basis of $R = 1.0$ prior to washing
R' = % solute remaining in the cake after washing on the basis of $R' = 100$ prior to washing
r = resistance of filter media, lines, etc.
S_0 = weight of solute originally present in the cake prior to washing
S_w = cumulative weight of solute in the wash filtrate
t = time
t_f = cake-formation time
t_w = cake-washing time
V = volume of filtrate at any time t
V_f = volume of filtrate at time t_f
V_l = volume of liquor in cake prior to washing
V_w = volume of wash filtrate
w = weight of dry cake solids per unit volume of filtrate
X = weight fraction of liquor in cake prior to washing
Z = form-filtration rate expressed as volume of filtrate or weight of dry-cake solids per unit area per hour of cake-formation time
α = specific cake resistance
$-\Delta P$ = pressure drop across filter
μ = liquid viscosity
ρ_c = density of wet cake prior to washing
ρ_l = density of liquor in cake

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