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Water Conservation in Industrial Filtration Operations

By

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Arkansas Water Resources Research Center

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WATER CONSERVATION IN INDUSTRIAL FILTRATION OPERATIONS

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September 30, 1977

* Note: Computer documentation of the work described herein is available upon request from the Arkansas Water Resources Research Center, University of Arkansas, Fayetteville, Arkansas, 72701

ABSTRACT

The washing of a solute from filter cakes was investigated for both saturated and unsaturated washing conditions. Systems used in this experimental study were 0.065 NaCl solution as the filtrate in an aluminum hydrate filter cake and 0.1 Normal HCl solution as the filtrate in a column packed with glass beads. The filtrate concentration as a function of the flow rate of wash water and of the volume of effluent from the packed bed was measured.

The amounts of filtrate removed from the bed during saturated washing and washing employing repetitive steps of saturation followed by evacuation were compared. Also, the amounts of wash water required to lower the filtrate concentration to essentially zero were contrasted. It was determined that the saturated wash condition was more efficient in removing the filtrate from compressible cakes, while the reverse was true for porous, incompressible cakes.

Computer programs were developed to simulate both saturated and unsaturated washing conditions.
Key Words: Filter Cake Washing, Saturated Washing, Unsaturated Washing

FURTHER ACKNOWLEDGEMENTS

This study was performed and completed with the assistance of many individuals.

Mr. Mike Newton chose this research project as the topic of his master's thesis, and did much of the experimental work. Others who helped with the experimental work were Mr. Wayne McCafferty, Mr. John Parks, and Mr. Mike Mourot.

The entire faculty of the Chemical Engineering Department of the University of Arkansas offered assistance on various phases of the project. Dr. James Lea of the Engineering Science Department of the University of Arkansas provided valuable input in the numerical solution of the partial differential equations describing the filtrate washing operation.

Supportive assistance was provided by the University of Arkansas. Key administrative individuals include: Dr. Robert E. Babcock, Director of the Water Resources Research Center; Dr. Loren R. Heiple, Dean of the College of Engineering, and Dr. James R. Couper, Head of the Chemical Engineering Department.

Reynolds Metals Company provided materials which were essential to the completion of the project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Washing of cake in filters takes place in three steps. First, the wash water displaces a considerable amount of the filtrate in the filter cake. During this first step of washing, the filtrate is not diluted by the wash water. In the second stage of washing, the filtrate is diluted by the wash water and filtrate concentration in the stream leaving the cake decreases continuously. Finally, the filtrate is slowly leached from the voids of the cake.

One example of an industry in which filtration operations play a large role is the alumina industry of Arkansas. Most washing on industrial filters is done by spraying the filter with water and then removing the water by pulling a vacuum on the filter. In some operations, this procedure is repeated several times until the desired wash is obtained. In this manner of filter washing, a portion of the water is used to refill the voids in the filter cake. Because of this refilling, some channels in the filter are washed and evacuated several times before the desired wash is obtained.

As air is introduced into the filter cake, tensions appear at the interface of the air and the filtrate in the voids of the cake. As the saturation decreases, the tensions at the interface increase and eliminate flow through the smaller channels of the packed bed.

In the past, water for filter washing has been readily available and relatively inexpensive. Because of this abundance of water, most filtration operations have been designed to use wash water far in excess of the minimum required to obtain a specified wash.

Use of large quantities of wash water means discharge of large quantities of water containing the materials which are washed from the filter cake.

Many industries utilize a closed system for process and wash water in which the water is recycled and fresh water is added only as make up. In order to conserve water and to reduce effluent, which requires further processing, the wash cycle should be optimized. Optimization of the filter washing cycle means great savings in terms of the energy, materials, and equipment required for processing the recycled wash water.

It appears that the practical limit of washing by displacement, which requires minimum wash water, is achieved by keeping the medium saturated during the washing. Also, if the cake were continuously saturated, the rate at which wash should be applied could be estimated from the final filtration rate.

ACHIEVEMENT OF PROJECT OBJECTIVES

A. Objectives

The primary objective of this project was to develop the means by which wash water could be conserved in industrial filtration operations. Conservation can be realized by providing the following information for a specific filter washing operation:

(1) A comparison of washing at continuously saturated conditions with washing employing repetitive steps of saturation followed by evacuation.

(2) At saturated conditions, how much more water than the direct displacement amount is needed to reach a specified effluent and/or residual concentration.

B. Extent of Achievement

The primary objective has been achieved. Mathematical models describing the washing of a filter cake have been developed for both the saturated and the unsaturated cases. Computer programs have been written for each of the two models. These computer solutions provide the information required for evaluation of filter washing operations.

However, a completely theoretical solution of the washing operation is not possible at this point. Each of the models requires experimental evaluation of certain parameters (e.g., porosity, dispersion coefficient). Also, more work is needed to adequately describe the physical mechanism and to reduce the number of experimental parameters required for solution of the unsaturated case.

REVIEW OF THE LITERATURE

A review of the literature includes washing operations in both continuous and batch filtration. Models and equations have been developed which correlate various process variables such as wash time, wash flow rate, final liquor concentration in the cake, bed porosity, etc.

Rhodes (1) correlated data concerning the washing of the cake in a leaf filter press with the equation:

$$\frac{KW}{V} = \frac{KW'}{V} e^{-KFt'/L} \qquad (1)$$

where K is an experimentally determined equilibrium constant. This relation predicted the wash time needed to lower a known filtrate concentration in the cake to a lower, desired level.

Crosier and Brownell (2) determined that porosity and shape (sphericity) of the packing do not have an appreciable influence on filter washing and that the diameter of the particles is the only significant variable. The investigators also developed the equation:

$$V_w = W_2 (V_f)_i = \gamma(\delta) W_2' (V_f)_i \qquad (2)$$

where γ and δ are multiplying factors which account for the effect of viscosity and channeling.

Cake washing on continuous filtration equipment was investigated by Choudbury and Dahlstrom (3). Assuming constant cake thickness, the following equation was derived:

$$R = \frac{1}{k} e^{-k(V_w/V_L)} \qquad (3)$$

where k is a constant equal to

$$\frac{K\rho_c y}{\rho_1}$$

Equation 3 indicates that a semilog plot of log R vs V_W/V_L should yield a straight line relationship.

Also the investigators determined that

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

where E_o is the wash efficiency (found to be 35%-86%) and n is the ratio of the volume of wash fluid per unit volume of original liquor in the unwashed cake. The lower wash efficiencies (E≈35%) were experienced in cakes which wash rapidly (e.g., long fiber cakes used in paper making.)

Once the wash ratio (n) had been determined, the final product purity and recovery per stage could be calculated.

Sherman (4) used a one dimensional, diffusionlike, partial differential equation in which the molecular diffusion coefficient was replaced by a longitudinal dispersion coefficient (D_L) to describe the movement of the soluble material through the packed bed. The bed was packed with a non-porous, granular material. The equation is as follows:

$$\frac{\partial c}{\partial t} = - u \frac{\partial c}{\partial z} + D_L \frac{\partial^2 c}{\partial z^2} \qquad (4)$$

Once a bed has been selected, the ratio, D_L/u, which is a mixing parameter, remained constant.

Han and Bixler (5) developed a blind side channel model for the filter cake. One assumption was that the bed is made up of a bundle of parallel capillaries with blind side channels. Also, it was assumed that the wash liquid passes in plug flow down through the straight channels with a plug flow velocity profile and displaces solute by molecular diffusion from the blind side channels.

The blind side channel model is shown in Figure 1.

The investigators solved the following equation for the straight channels:

$$\frac{\partial \mu}{\partial t} + V' \frac{\partial \mu}{\partial z} = aN \quad (5a)$$

and

$$\frac{\partial c(\theta, x)}{\partial \theta} = \frac{D \partial^2 c(\theta, x)}{\partial x^2} \quad (5b)$$

for the side channels.

The equation derived was:

$$F_o = 1 - e^{-KW_6} \quad (6)$$

where K is a type of mass transfer coefficient and F_o is the fraction of residual liquid washed.

A mathematical model to describe the washing performance of partially drained filter and centrifuge cakes was developed by Wakeman and Rushton (6). The investigators concluded that cake washing processes need to be represented by a number of theoretical models depending on the age of the process and operating conditions. The equation developed showed that C/C_o was a function of the Peclet number, void volumes of wash liquor, and the L/d ratio of the packing.

Silverblatt, Risbud, and Tiller (7) plotted $(C_o - C)/(C_o - C_W)$ vs. wash ratio. Initially, the function $(C_o - C)/(C_o - C_W)$ is constant and decreases as the volume of wash water increases.

These investigators concluded from their experiments that the efficiency of the wash drops considerably when diffusion washing starts. Also, it was concluded that in beds of high porosity and low resistance, it is difficult to remove over 90% of the original liquor.

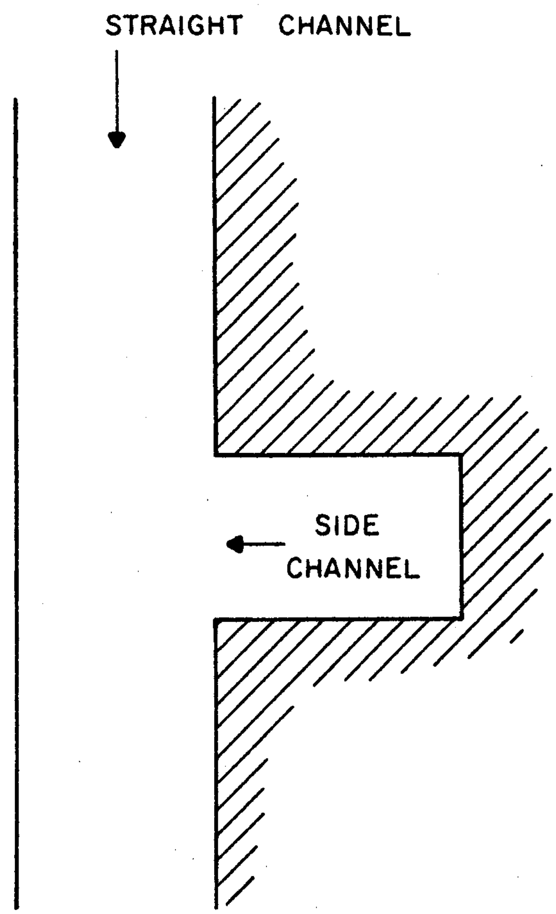

FIGURE 1. BLIND SIDE CHANNEL MODEL

DEVELOPED BY HAN AND BIXLER (5)

THEORETICAL ANALYSIS

Upon examination of washing in filtration operations, a number of different models are noted. The model chosen for this investigation is similar to the blind side channel model developed by Han and Bixler (5). This model assumes that the packed bed is made up of a bundle of parallel capillaries with blind side channels. Also, it assumes that the liquid passes in plug flow through the straight channels (capillaries) and displaces filtrate by diffusion from the side channels.

The bed representation for this investigation is shown in Figure 2.

Referring to Figure 2, the material balance for the solute in the active channels is:

$$m\Big|_E - m\Big|_B = \dot{m}\Big|_{in}\Delta t - \dot{m}\Big|_{out}\Delta t + \dot{m}_{source}\,\Delta t\,\Delta L \tag{7}$$

Considering dispersion and diffusion this equation may be rewritten as:

$$\begin{aligned} c'\rho\varepsilon_a A\Delta z\Big|_{t+\Delta t} - c'\rho\varepsilon_A A\Delta z\Big|_t &= c'\rho Q\Delta t\Big|_z - c'\rho Q\Delta t\Big|_{z+\Delta z} \\ &+ D_t\rho A\varepsilon_A\left(\frac{-\Delta c'}{\Delta z}\right)\Delta t\Big|_z - D_t\rho A\varepsilon_A\left(\frac{-\Delta c'}{\Delta z}\right)\Delta t\Big|_{z+\Delta z} \\ &+ \dot{m}_{source}\,\Delta t\,\Delta z \end{aligned} \tag{8}$$

Dividing by $\Delta z\Delta t$ and taking the limit as $\Delta t \to 0$ and $\Delta z \to 0$ yields:

$$\frac{\partial(c'\rho\varepsilon_a A)}{\partial t} = \frac{-\partial(c'\rho Q)}{\partial z} - \frac{\partial[D_t\rho A\varepsilon_a(-\frac{\partial c'}{\partial z})]}{\partial z} + \dot{m}_{source}$$

For the contribution of the source term, a mass transfer coefficient approach was used;

$$\dot{m}_{source} = k_D A_D\left(\frac{C_D\rho}{M} - \frac{c'\rho}{M}\right)M \tag{9}$$

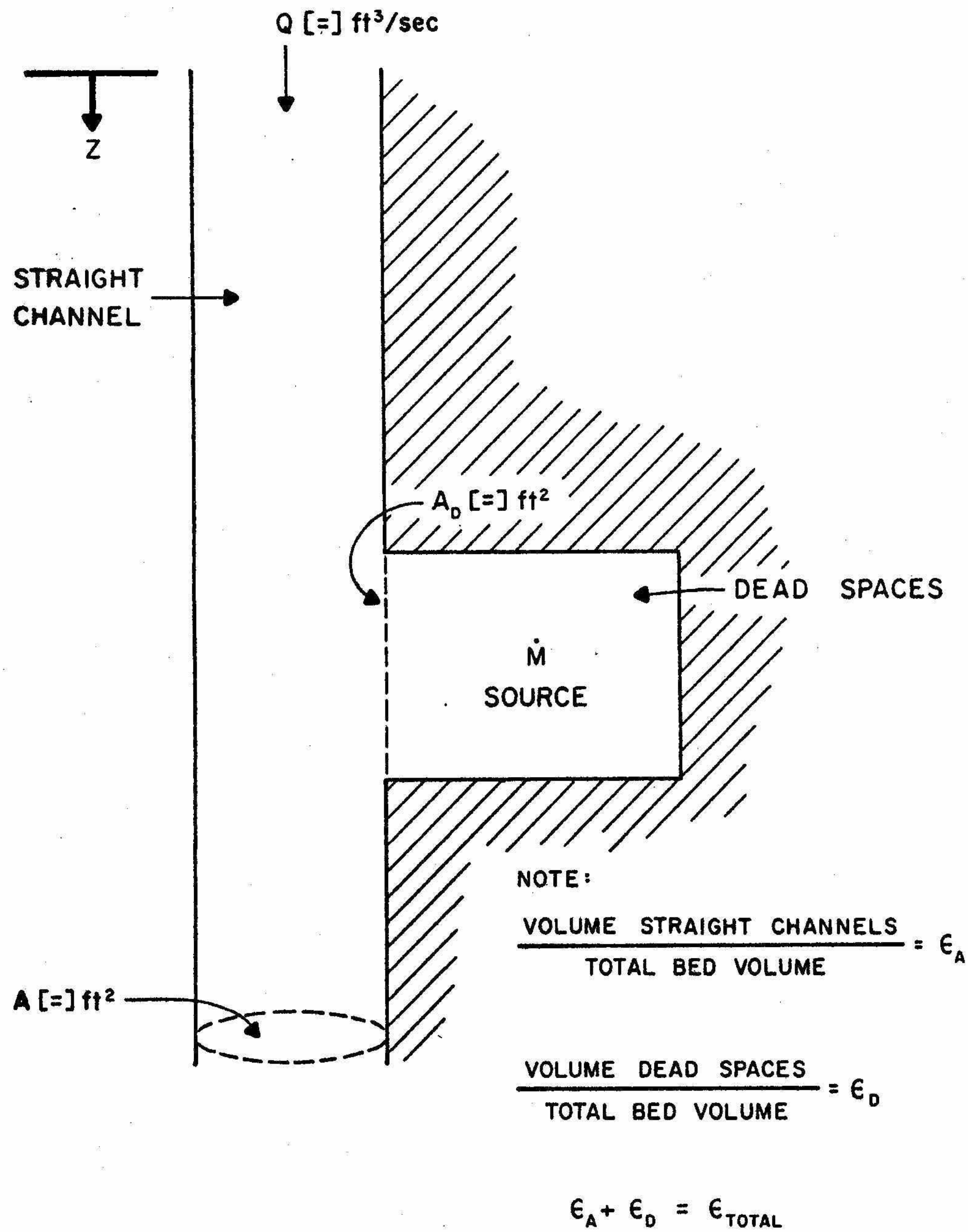

FIGURE 2.
CONTROL VOLUME FOR THEORETICAL ANALYSIS

where C_D is the concentration of filtrate in the dead space. It is assumed that the concentration in the dead space decays exponentially according to:

$$C_D = C_{DO} e^{-k' t_D} \tag{10}$$

C_{DO} is the initial concentration of the filtrate in the dead spaces and k' is a parameter ($\sec^{-1}$).

If plug flow is assumed, the velocity of the liquid passing through the bed equals

$$\frac{Q}{A\varepsilon_a} \qquad (U \text{ plug}) \tag{11}$$

Also for plug flow,

$$t_D = t - \frac{z}{U \text{ plug}} \tag{12}$$

This equation gives the relationship between t, time from the initiation of wash, and t_D, the length of time of mass transfer from the dead spaces.

The equation describing the wash of the filtrate from the bed is

$$\frac{\partial}{\partial t}(c'\rho\varepsilon_a A) = -\frac{\partial(c'\rho Q)}{\partial z} - \frac{\partial[D_t \rho A \varepsilon_A (-\frac{\partial c'}{\partial z})]}{\partial z} + k_D A_D \left(\frac{C_{DO} e^{(-k' t_D)} \rho}{M} - \frac{c'\rho}{M}\right) M \tag{13}$$

If the filtrate in the filter cake is a dilute solution, it may be assumed that the density of the solution in the bed remains constant. Also, it is assumed that the bed and fluid properties remain constant. The wash equation then becomes;

$$\rho\varepsilon_a A \frac{\partial c'}{\partial t} = -\rho Q \frac{\partial c'}{\partial z} + D_t \rho A \varepsilon_A \frac{\partial^2 c'}{\partial z^2} + k_D A_D \left(\frac{C_{DO} e^{(-k' t_D)} \rho}{M} - \frac{c'\rho}{M}\right) M \tag{14}$$

Dividing both sides of the equation by $\rho\varepsilon_a A$ the wash equation becomes

$$\frac{\partial c'}{\partial t} = -\frac{Q}{\varepsilon_a A} \frac{\partial c'}{\partial z} + D_t \frac{\partial^2 c'}{\partial z^2} + \frac{k_D A_D}{\rho\varepsilon_a A} \left(\frac{C_{DO} e^{(-k' t_D)} \rho}{M} - \frac{c'\rho}{M}\right) M \tag{15}$$

The constant groups are redefined as follows:

$$\alpha = \frac{-Q}{\varepsilon_A A}$$

$$\beta = D_t$$

$$\gamma = \frac{k_D A_D}{\rho \varepsilon_a A}$$

Therefore,

$$\frac{\partial c}{\partial t} = \alpha \frac{\partial c}{\partial z} + \beta \frac{\partial^2 c}{\partial z^2} + \gamma \left(\frac{C_{DO} e^{(-k' t_D)} \rho}{M} - \frac{c' \rho}{M} \right) M \qquad (16)$$

This partial differential equation was solved numerically...

Let $C_{i,j} = C_{time,distance}$

By difference equation methods, the derivatives may be estimated as follows:

$$\frac{\partial c}{\partial t} = \frac{C_{i,j} - C_{i-1,j}}{\Delta t} \qquad (17)$$

$$\frac{\partial c}{\partial z} = \frac{C_{i-1,j+1} - C_{i-1,j}}{\Delta z} \qquad (18)$$

$$\frac{\partial^2 c}{\partial z^2} = \frac{C_{i-1,j+1} - 2C_{i-1,j} + C_{i-1,j-1}}{\Delta z^2} \qquad (19)$$

With these numerical approximations for the derivatives the wash equation may be written to give a value for the filtrate concentration at a particular time and distance in the column.

$$C_{i,j} = C_{i-1,j} + \Delta t \left\{ \alpha \left(\frac{C_{i-1,j+1} - C_{i-1,j}}{\Delta z} \right) + \beta \left(\frac{C_{i-1,j+1} - 2C_{i-1,j} + C_{i-1,j-1}}{\Delta z^2} \right) + \gamma \left(\frac{C_{DO} e^{-k' t_D} \rho}{M} - \frac{C_{i,j} \rho}{M} \right) M \right\} \qquad (20)$$

In the unsaturated case, the filter cake has been drained, with filtrate remaining in the dead spaces. Depending on the particular cake, there may or may not be residual filtrate in the open channels of the drained cake.

For saturated washing, if plug flow is assumed, the filtrate concentration ahead of the wash wave front would be equal to the initial filtrate concentrations. $C_{i,j}$ would equal $C_{i-1,j}$ until the wash wave front has passed. Also, $C_{i-1,j+1}$ would equal $C_{i-1,j}$ and $C_{i-1,j-1}$ until the wave front has passed. This is due to the fact that there is no concentration driving force for dispersion or diffusion until after the wave front has passed. The initial and boundary conditions of this equation for the saturated case are:

$C_{i,j} = C_0$ at $t = 0$

$C_{i,j} = 0$ for $t \to \infty$

$C_{i,1} = 0$ at $t > 0$

The initial and boundary conditions for the unsaturated case are as follows:

$C_{i,j}$ would be undefined until the wave front has passed

$C_{i,J} = 0$ as $t \to \infty$

$C_{1,j} = 0$ for $t > 0$

In the unsaturated case, at the initiation of wash no fluid is in contact with the filtrate in the dead spaces. The first fluid the dead space filtrate comes in contact with is the wash fluid. In this case, $C_{i,j}$ would be undefined until the wave front has passed. After the wash front has passed, diffusion and dispersion begin.

Computer simulations of saturated and unsaturated filter washings were developed. The variable parameters in the computer programs were D_t, k_D, k'. The values of D_t were estimated from a plot in Levenspiel (8).

It appears that:

$$k_D = \psi_1(N_{Re}, N_{Sc}, \varepsilon)$$

and

$$k' = \psi_2(N_{Re}, N_{Sc}, \varepsilon)$$

The variable parameters are determined experimentally for a given filter cake. They are then used in the computer simulation to predict curves for either saturated or unsaturated washing.

EXPERIMENTAL PROGRAM

General Considerations

The major objective of this investigation was to compare saturated washing and unsaturated washing of filter cakes. This was to be done by developing a mathematical model to describe the filter washing for each of the saturated and unsaturated cases.

Noting the general objective as outlined above, an overall experimental program was formulated, the fluid system and packing were chosen, and the equipment which is described in the next section was assembled.

Description of Experimental Apparatus:

The equipment used in this investigation consisted of a 3.08 inch (ID), 36-inch long plexiglas packed column, a Leeds-Northrup conductivity probe, and the related components and piping required to establish flow as well as measure the pressure in the column. Schematic diagrams of the experimental apparatus are shown in Figures 3 and 4. The column was piped so that the effluent from the column passed through the conductivity probe.

The conductivity probe was connected to a Hewlett-Packard strip chart recorder which recorded the probe's signal.

An aluminum wool pad was placed in the column just above the packed bed to distribute the flow of wash water and to prevent the water from disturbing the top portion of the bed.

Pressure was applied to the column by supplying air to the system above the packed bed. The air flow was obtained from the University of

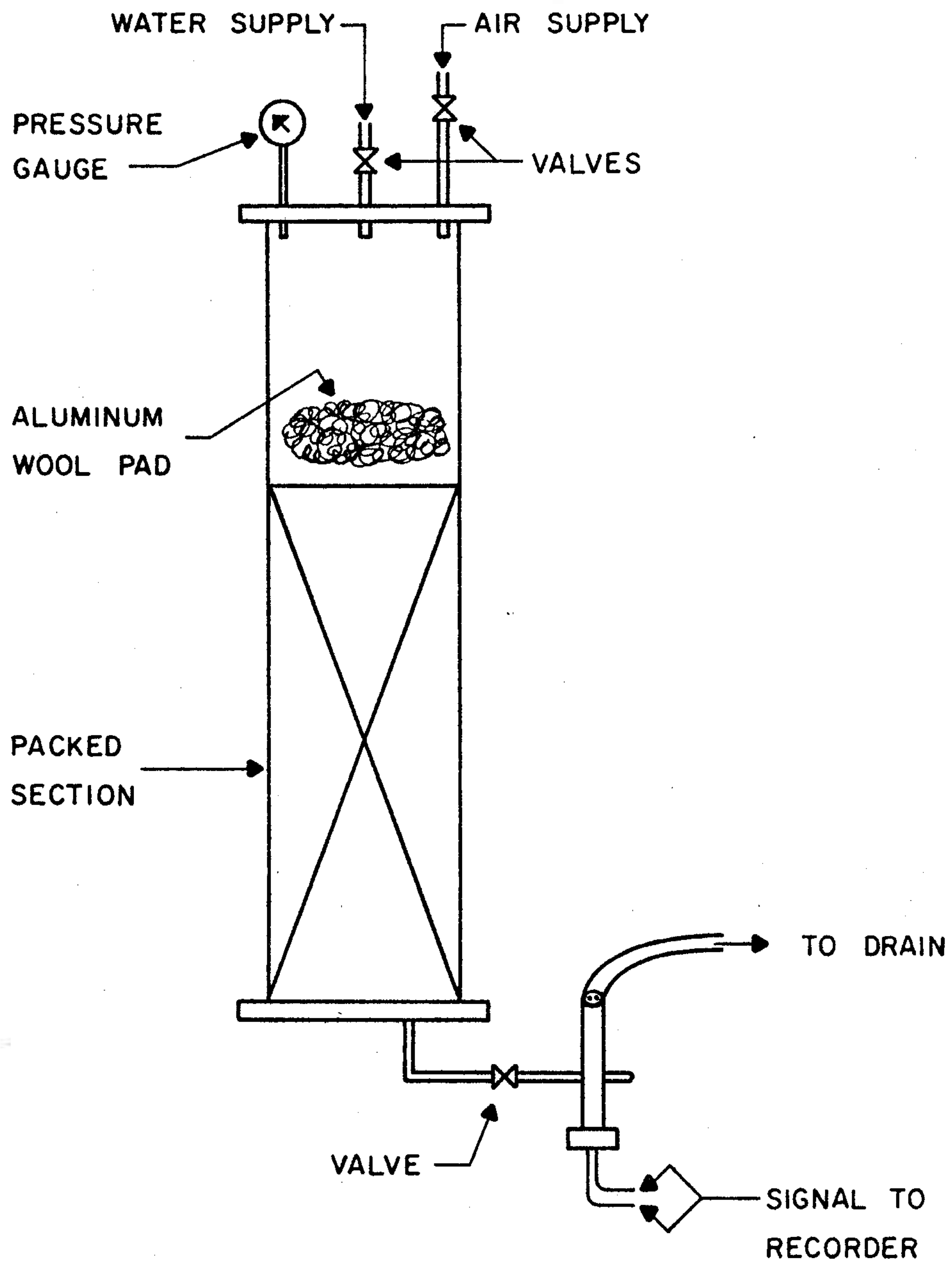

FIGURE 3.
SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS

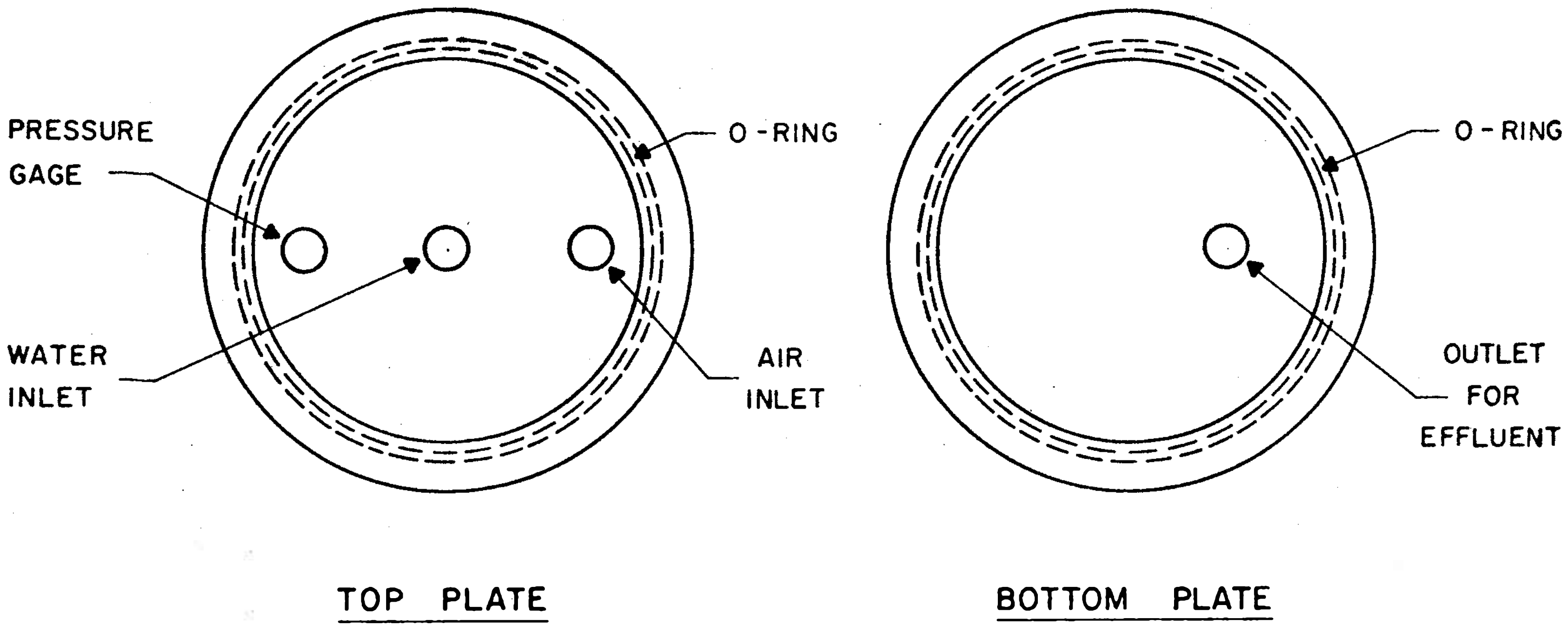

FIGURE 4. TOP AND BOTTOM PLATES

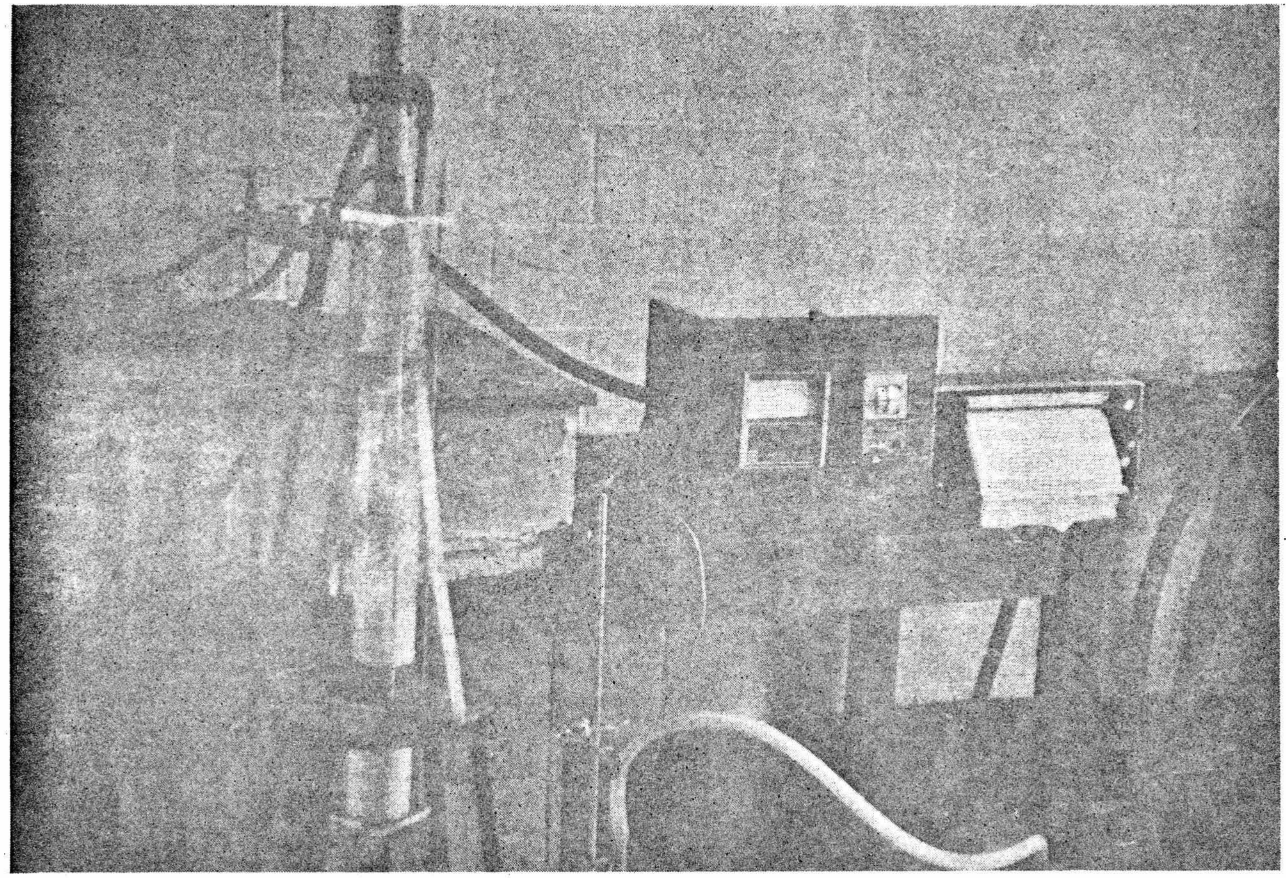

Figure 5. Photograph of the Experimental Apparatus

Arkansas Physical Plant air supply.

Wash water was supplied to the column continuously in the saturated washing case. In the unsaturated case, the top of the column was removed, the wash water added, and the top replaced. Both the top and bottom plates of the column were sealed by rubber "o" rings to prevent air and water leaks.

Operating Procedure:

Calibration of Equipment:

Prior to the taking of data, the conductivity probe and recorder required calibration. This calibration was made after a warm-up time of thirty minutes. The conductivity probe, which indicates salt concentration, was calibrated to read maximum, 10, when the salt concentration was equal to the concentration of the solution to be introduced into the column. This probe measures salt concentrations between 0 and 7 per cent. The probe was calibrated to give a zero reading when in contact with ordinary tap water.

The recorder was then calibrated to give the same reading as the conductivity probe. The time lag between the probe and the recorder were considered negligible (less than one second).

Packing of the Bed:

The plexiglas cylinder was partially filled with a known volume and concentration of salt solution. Packing was added slowly through the top of the column, while the side of the column was being tapped lightly with a rubber hammer to assure that the bed packing was consistent. The volume and weight of packing required to give a desired bed height were recorded each run to assure that the packing was essentially constant for each run. An aluminum wool pad was then placed in the column above the packing to prevent disturbance of the bed.

Operating Procedure: Saturated Wash:

When the desired bed height was reached, pressure was applied to the system and the salt solution removed until the level of the solution was even with the top of the packed section. The solution removed was collected and the amount and salt concentration recorded.

Pressure was then applied and wash water continuously added to the system from the water supply.

The flow rate of solution through the bed was determined by allowing the effluent passing through the probe to drain into a graduated cylinder for a measured length of time. This procedure was carried out three times during each run to assure that the flow rate remained constant throughout the run.

As the effluent passed through the probe, the reading was recorded on the strip chart.

When the salt concentration in the effluent reached essentially zero, the wash water and recorder were stopped.

From the recorded readings, a plot of C/C_o vs. volume through the bed was made. By graphical integration the amount of salt removed from the system during the wash cycle was determined. This information coupled with the amount and concentration of the solution removed from the bed prior to the run was used to make a material balance on the salt in the bed.

Operating Procedure: Unsaturated Wash:

When the desired bed height was obtained, pressure was applied to the system and salt solution completely drained from the system. This solution was collected and the concentration measured to determine the amount of solution remaining in the bed.

The top of the column was removed and one wash volume of tap water, determined by the porosity and volume of the packing, was added. The top was then replaced and pressure applied to the system. The effluent was passed through the conductivity probe until the entire wash volume had passed through the bed. The probe's reading was recorded in the same manner as for the saturated wash. When the entire wash volume had passed through the bed, the recorder and pressure were shut off. Approximately thirty seconds were required for the pressure in the system to drop to atmospheric.

The procedure of adding one wash volume and washing the bed was duplicated for two more wash volumes on each run.

The breakthrough time and the time needed for the entire wash volume to pass through the bed were read from the recorder (1 inch equals 10 seconds). The recorder speed was checked with a stop watch.

From the recorded data a plot of C/C_o vs. volume of solution through the bed was made.

A mass balance on the salt in the system was made using the washing curve and the information on the salt drained from the bed. The mass balance determined the amount of salt washed from the bed. The packing and bed properties may be found in Table 1.

Operating Procedure: Computer Program:

The computer programs describing both the saturated wash and unsaturated wash have three adjustable parameters. These parameters are D_t, k_D, k'. Adjusting D_t affects the upper portion of the washing curve. The parameters k' and k_D determine the rate at which the concentration decays in the dead spaces after displacement washing ends, and also the amount of filtrate which diffuses from the dead spaces.

Table 1.

Packing and Bed Properties

Bed Packing	Bed Height (ft)	Cross Section Area of Bed (ft^2)	Particle Diameter In.	ϵ_{total}	ϵ_{dead}	ϵ_{active}	Filtrate
Glass Beads	2	0.0513	0.1	0.372	0.01	0.362	0.1 N HCl
$Al_2O_3 \cdot 3H_2O$	1	0.0513	0.0029	0.48	0.11	0.37	0.065 NaCl

These three parameters were adjusted so that the washing curve predicted by the computer program matched the experimental curve.

A regression analysis (9) was run on the two parameters k' and k_D to determine a relationship between these parameters and the Reynolds number, Schmidt number and bed voidage. A good approximation of D_t was obtained from Levenspiel (8).

After the parameters were estimated and/or measured, a number of washing runs were simulated by the computer programs in order to compare saturated and unsaturated washings.

EXPERIMENTAL RESULTS

Results obtained from the preceding experimental program are presented in this section. The raw data from the experimental program are on file with the Chemical Engineering Department, University of Arkansas.

Experimental data showing the exit concentration as a function of the volume of effluent from the column are presented in Figures 6-13. Computer predictions of the wash curves for both saturated and unsaturated washings are compared to experimental wash curves in Figures 14-20.

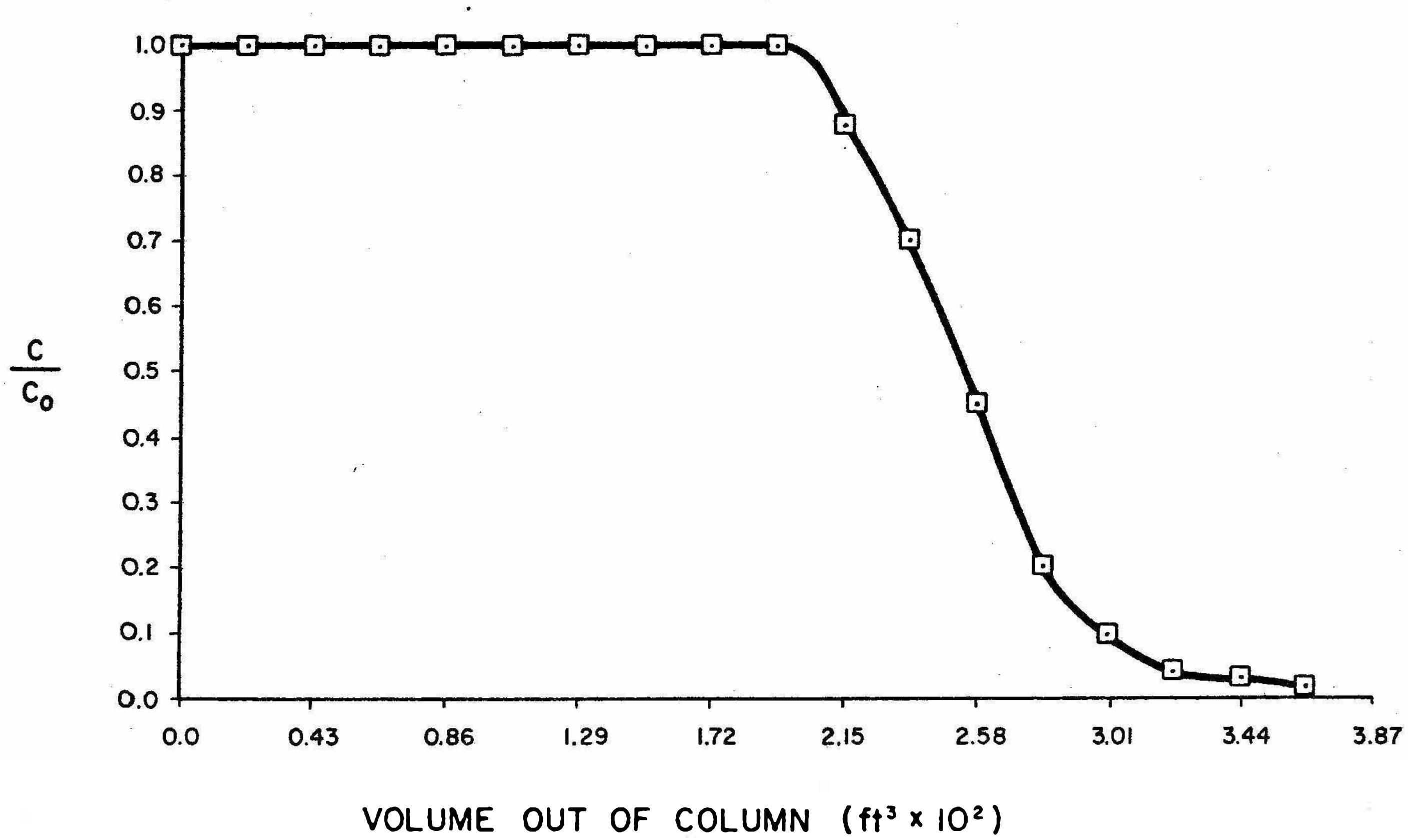

FIGURE 6. SATURATED WASH

RUN NO. 1S, FLOW RATE - 3.44×10^{-4} ft^3/sec.

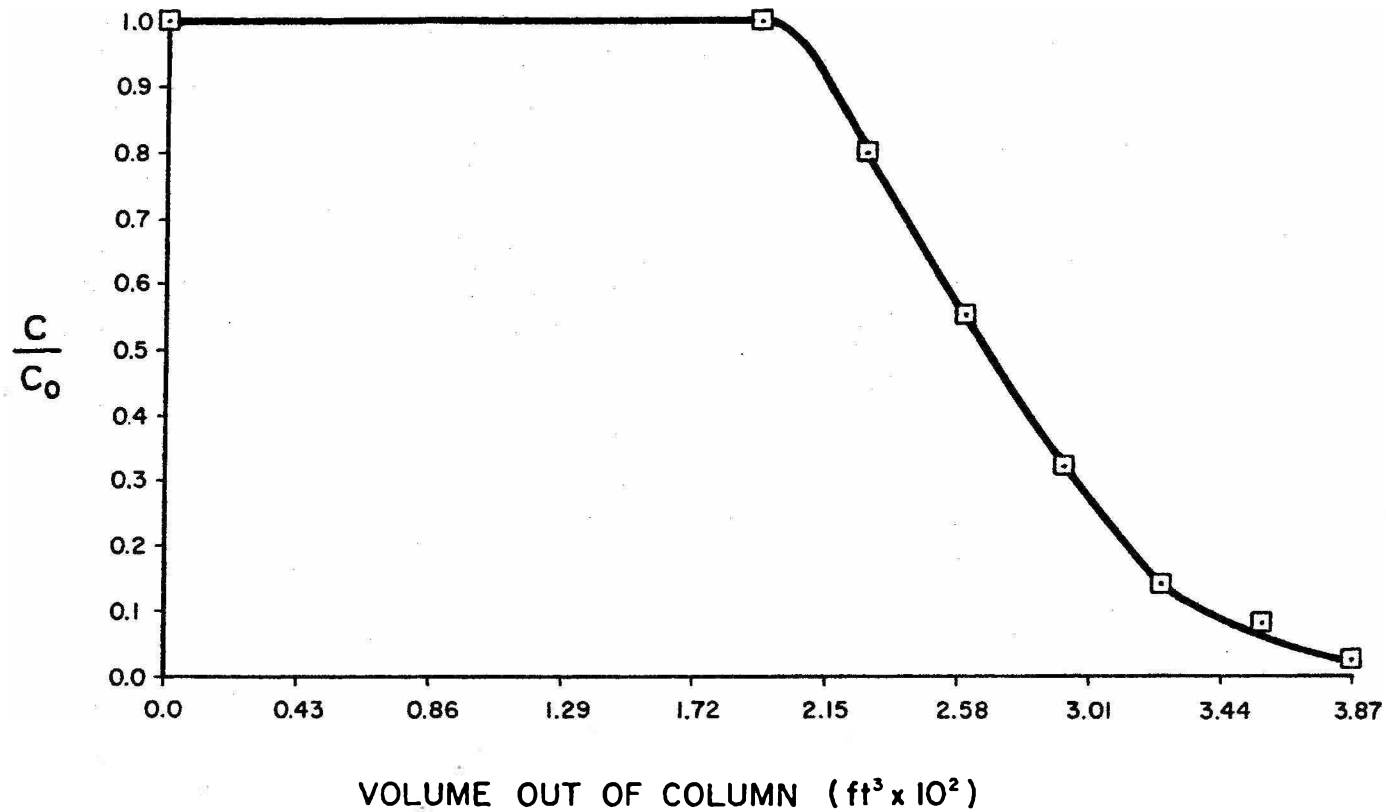

FIGURE 7. SATURATED WASH

RUN NO. 3S, FLOW RATE – 6.42×10^{-4} ft.³/sec.

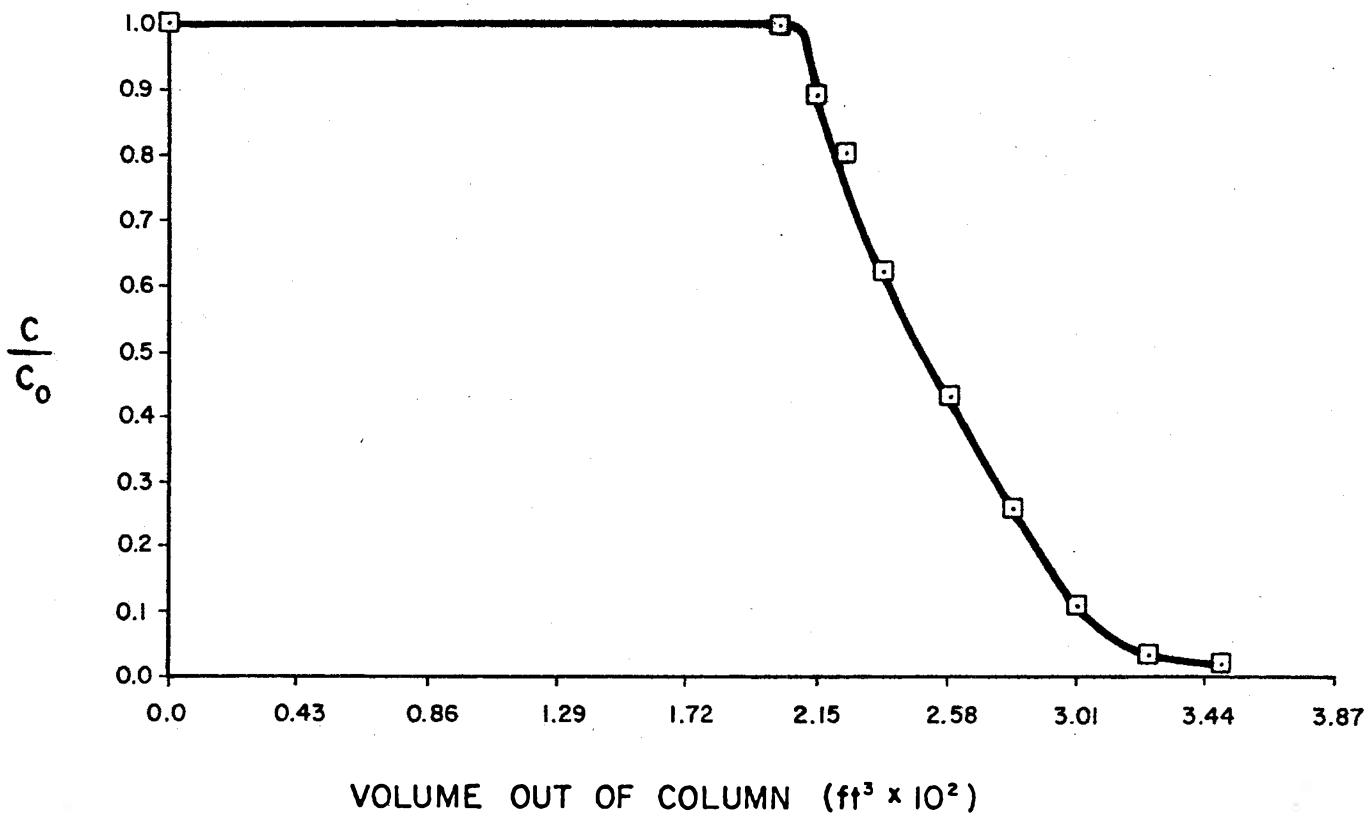

FIGURE 8. SATURATED WASH

RUN NO. 5S, FLOW RATE – 1.09 x 10^{-4} ft^3/sec.

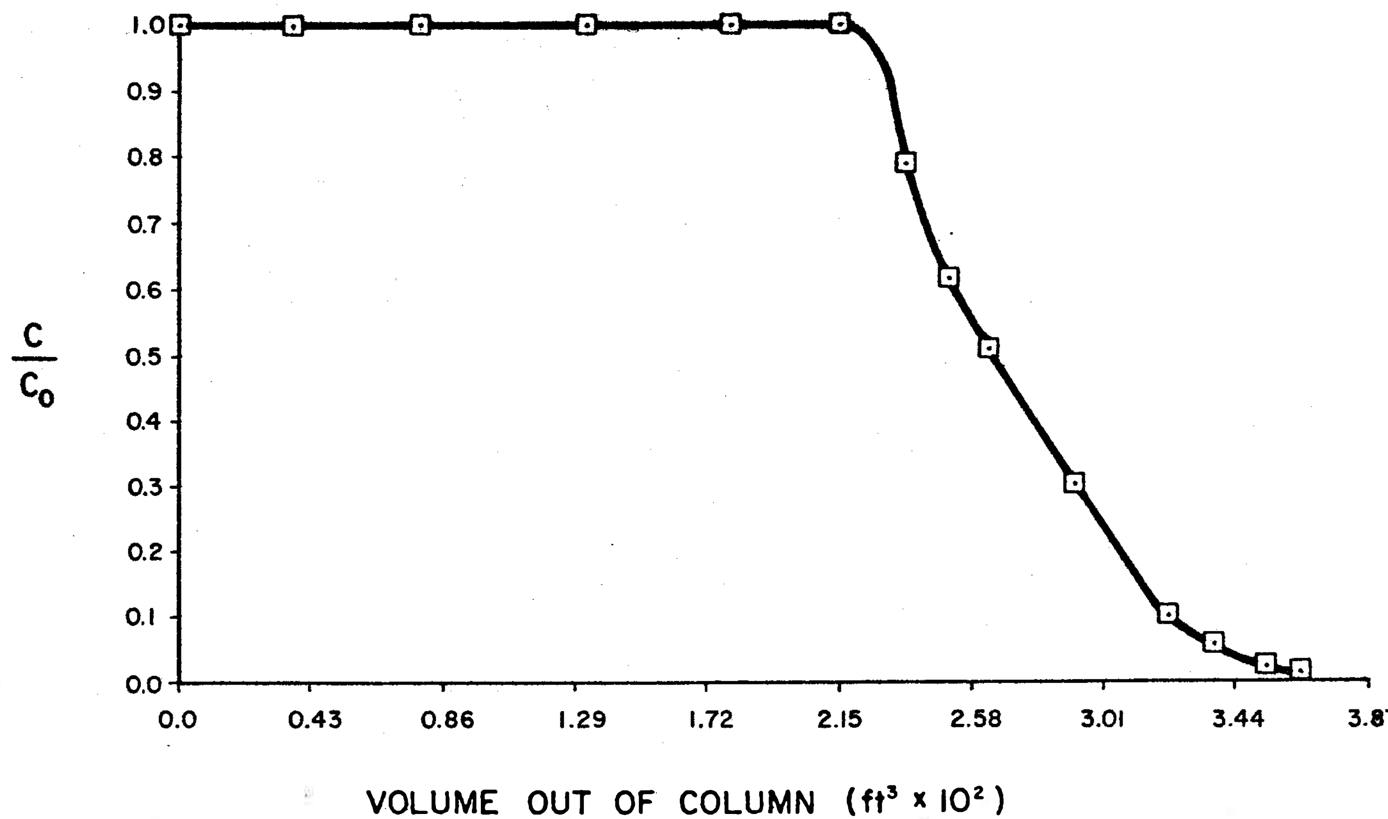

FIGURE 9. SATURATED WASH

RUN NO. 6S, FLOW RATE – 2.86×10^{-4} ft^3/sec.

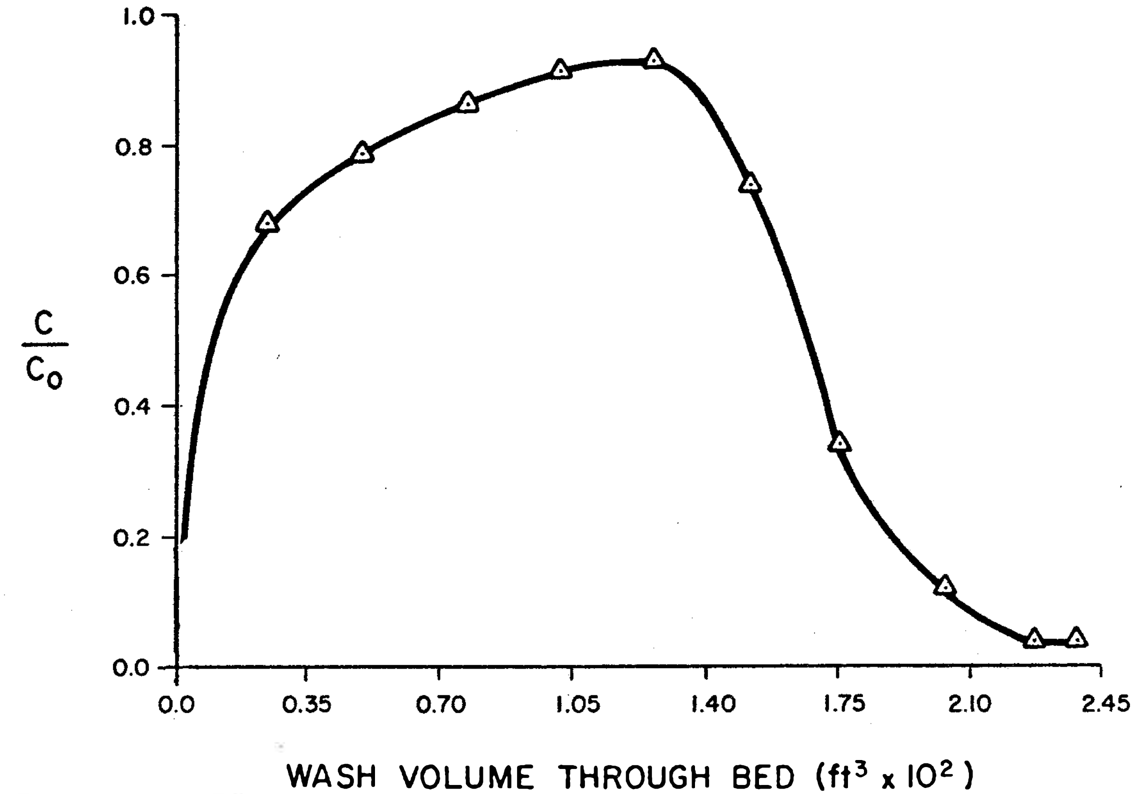

FIGURE 10. UNSATURATED WASH

WASH VOLUME NO. 1, RUN NO. 1

FLOW RATE — 5.12×10^{-4} ft^3/sec.

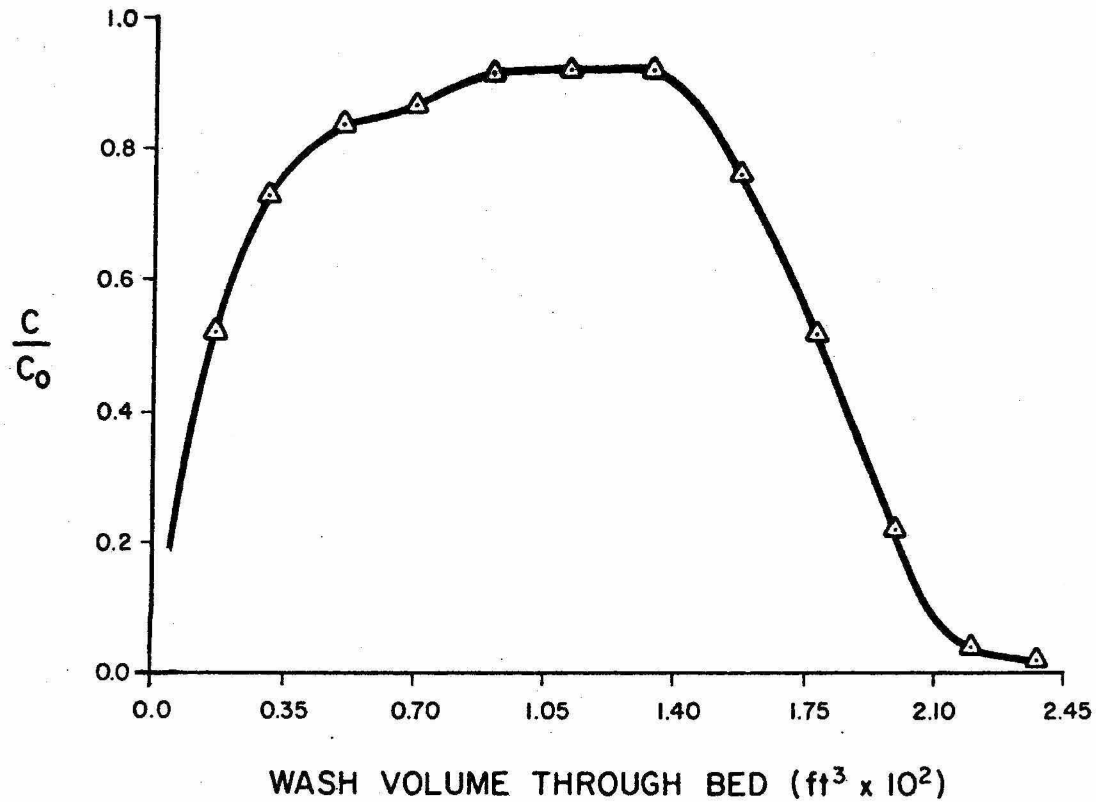

FIGURE II. UNSATURATED WASH

WASH VOLUME NO. 1, RUN NO. 2
FLOW RATE — 4.27 x 10^{-4} ft.³/sec.

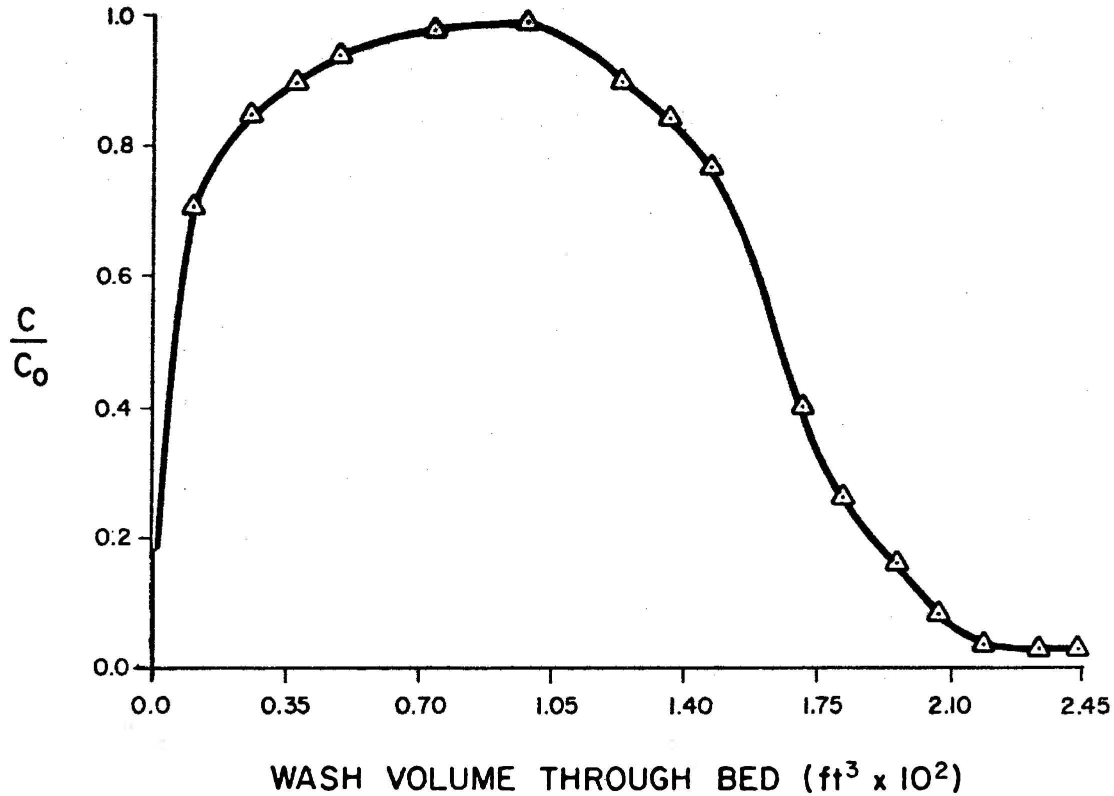

FIGURE 12. UNSATURATED WASH

WASH VOLUME NO. 1, RUN NO. 4

FLOW RATE – 2.47 x 10^{-4} ft^3/sec.

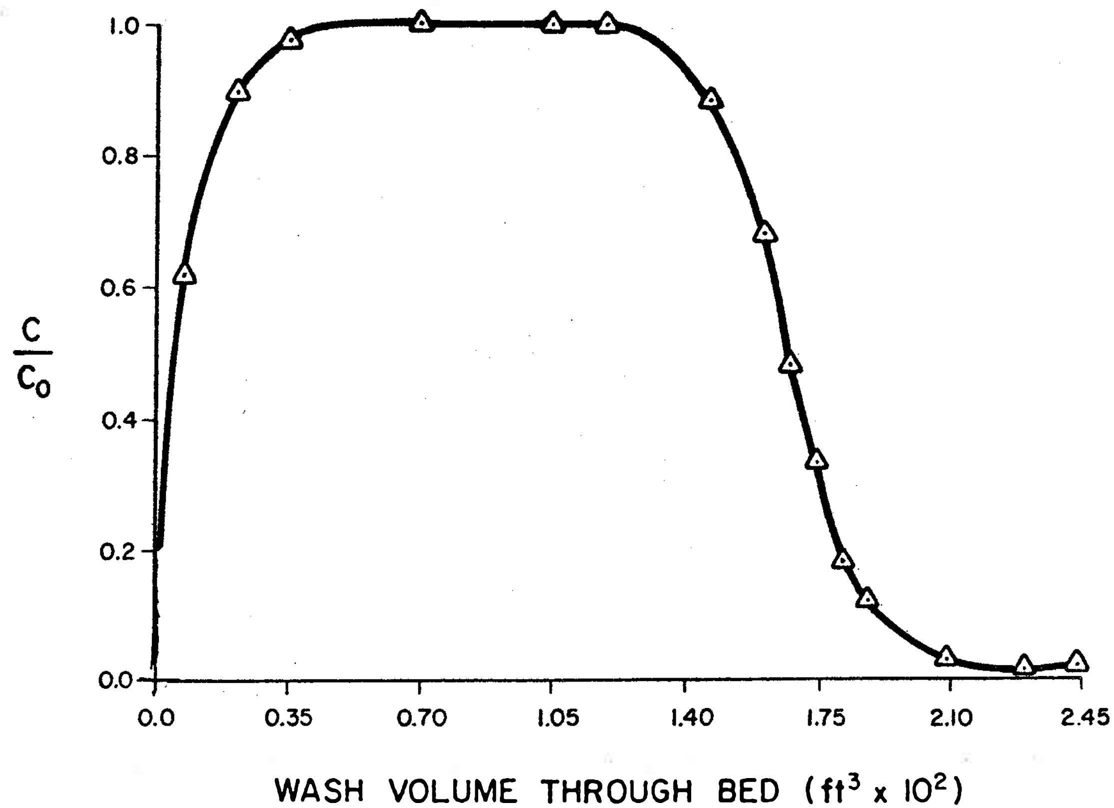

FIGURE 13. UNSATURATED WASH

WASH VOLUME NO. 1, RUN NO. 5

FLOW RATE — 0.70 x 10^{-4} ft.^{3}/sec.

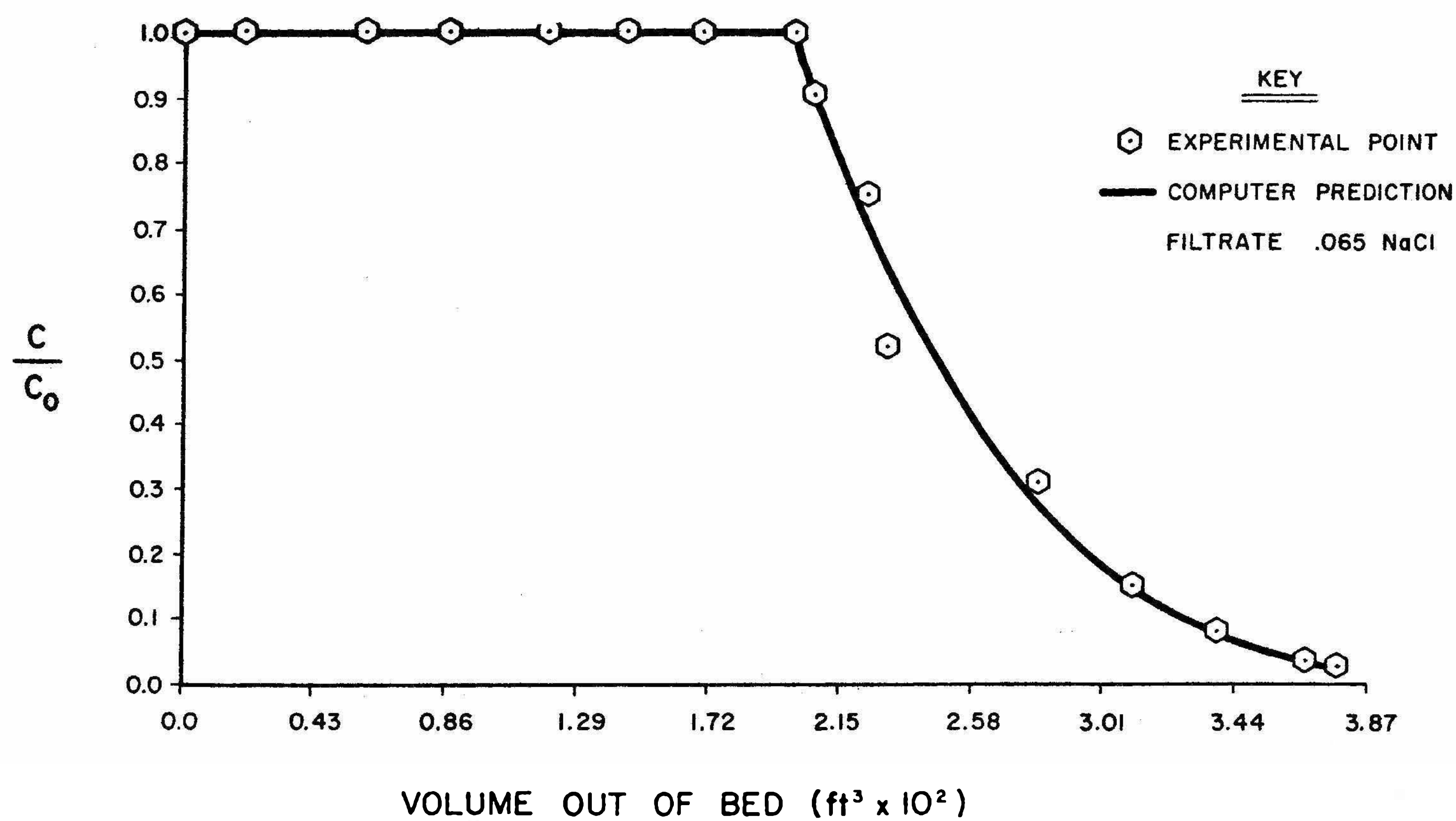

FIGURE 14. SATURATED WASH

RUN NO. 1S, FLOW RATE – 3.45×10^{-4} ft^3/sec.

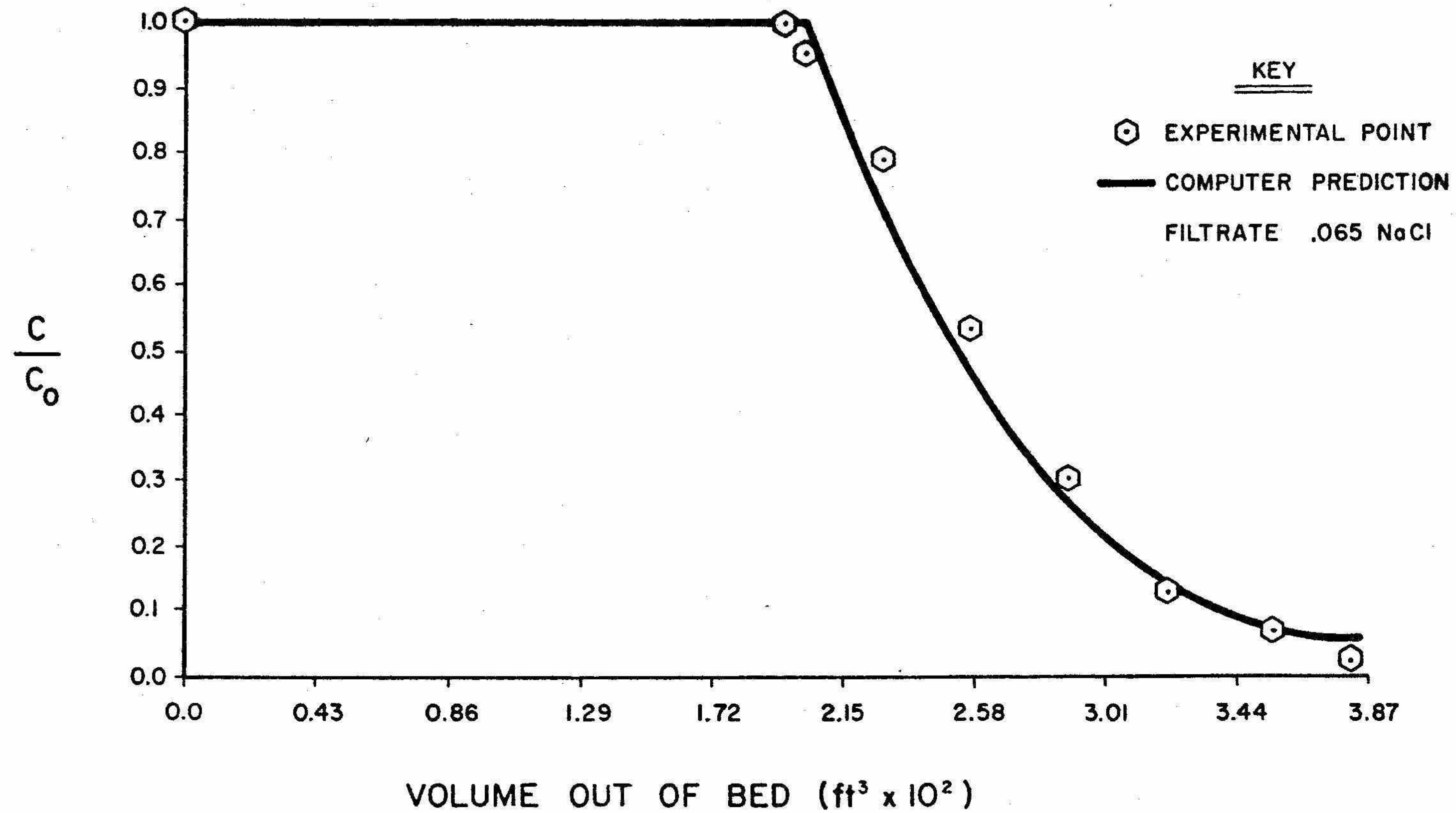

FIGURE 15. SATURATED WASH

RUN NO. 3S, FLOW RATE - 6.40 x 10^{-4} ft^3/sec.

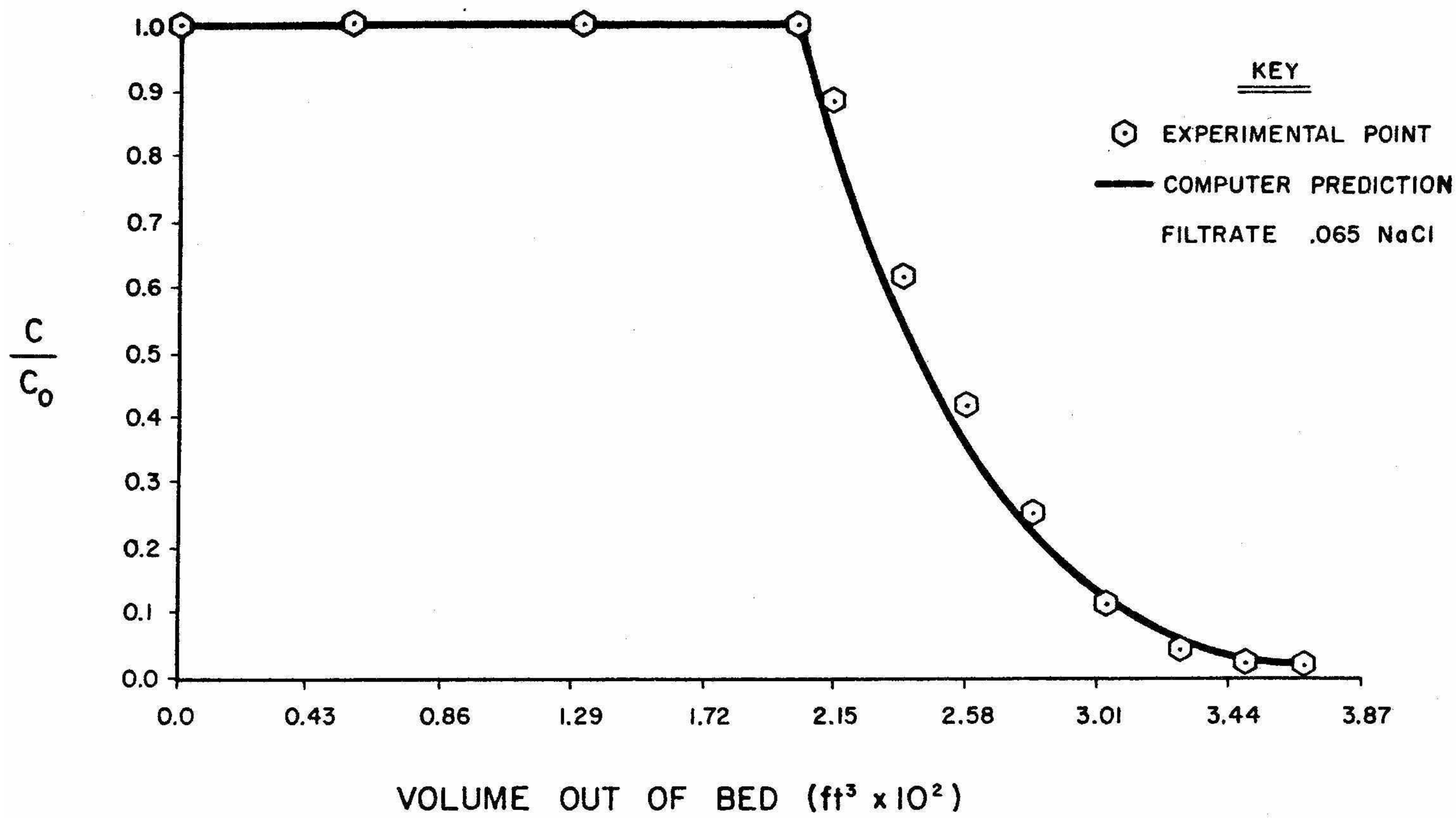

FIGURE 16. SATURATED WASH

RUN NO. 5S, FLOW RATE – 1.09 x 10^{-4} $ft.^3$/sec.

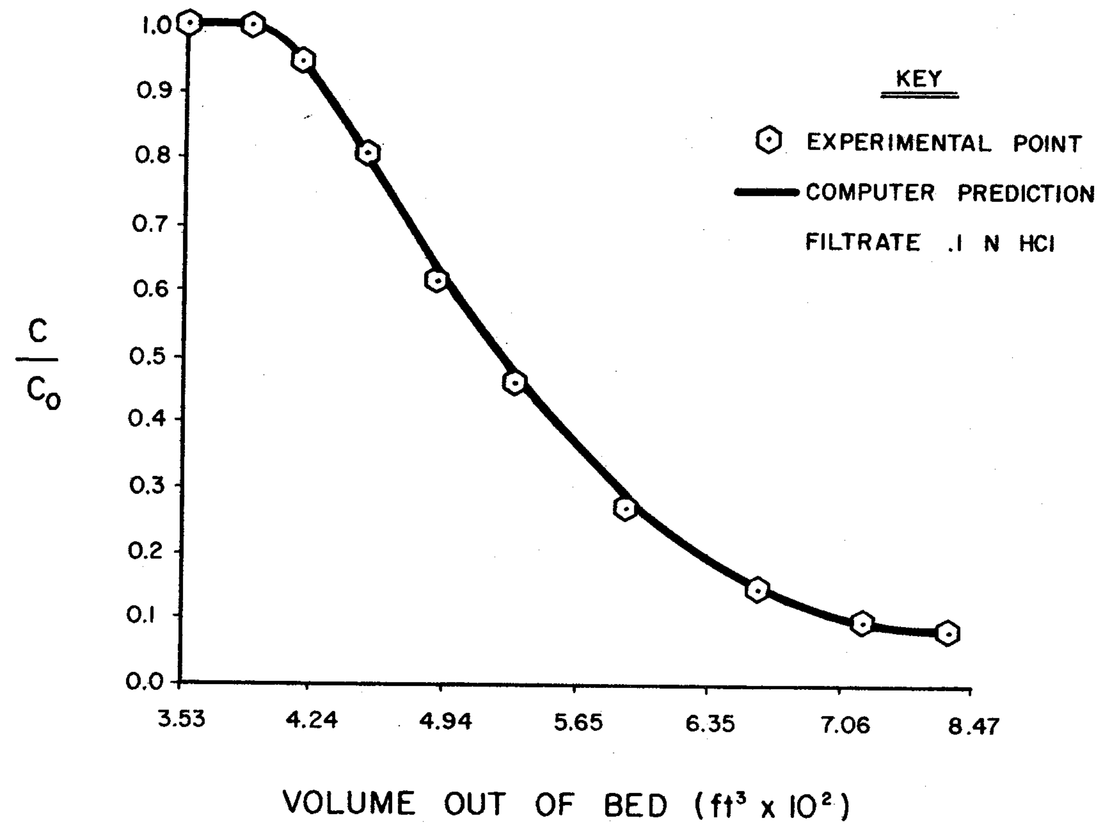

FIGURE 17. SATURATED WASH

RUN NO. 7, FLOW RATE – 1.76×10^{-4} $ft.^3$/sec.

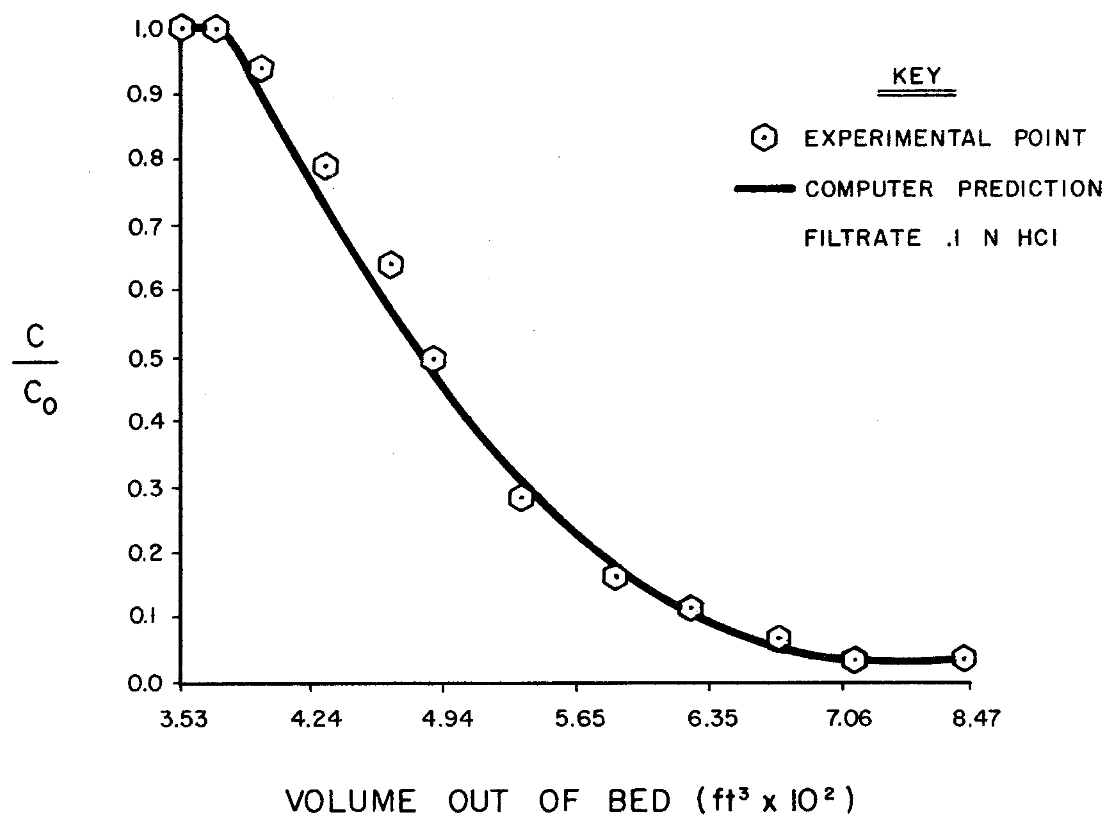

FIGURE 18. SATURATED WASH

RUN NO. 8, FLOW RATE — 3.52 x 10^{-4} ft^3/sec.

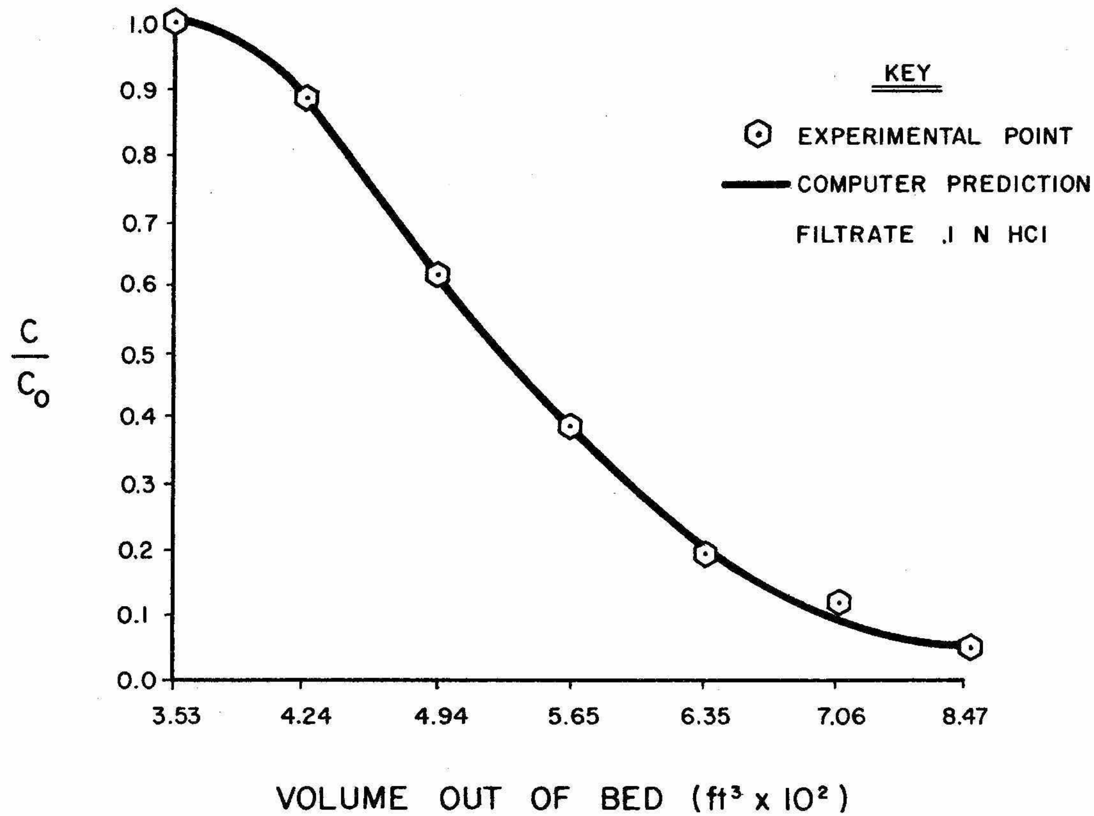

FIGURE 19. SATURATED WASH

RUN NO. 11, FLOW RATE — 2.35 x 10^{-4} ft^3/sec.

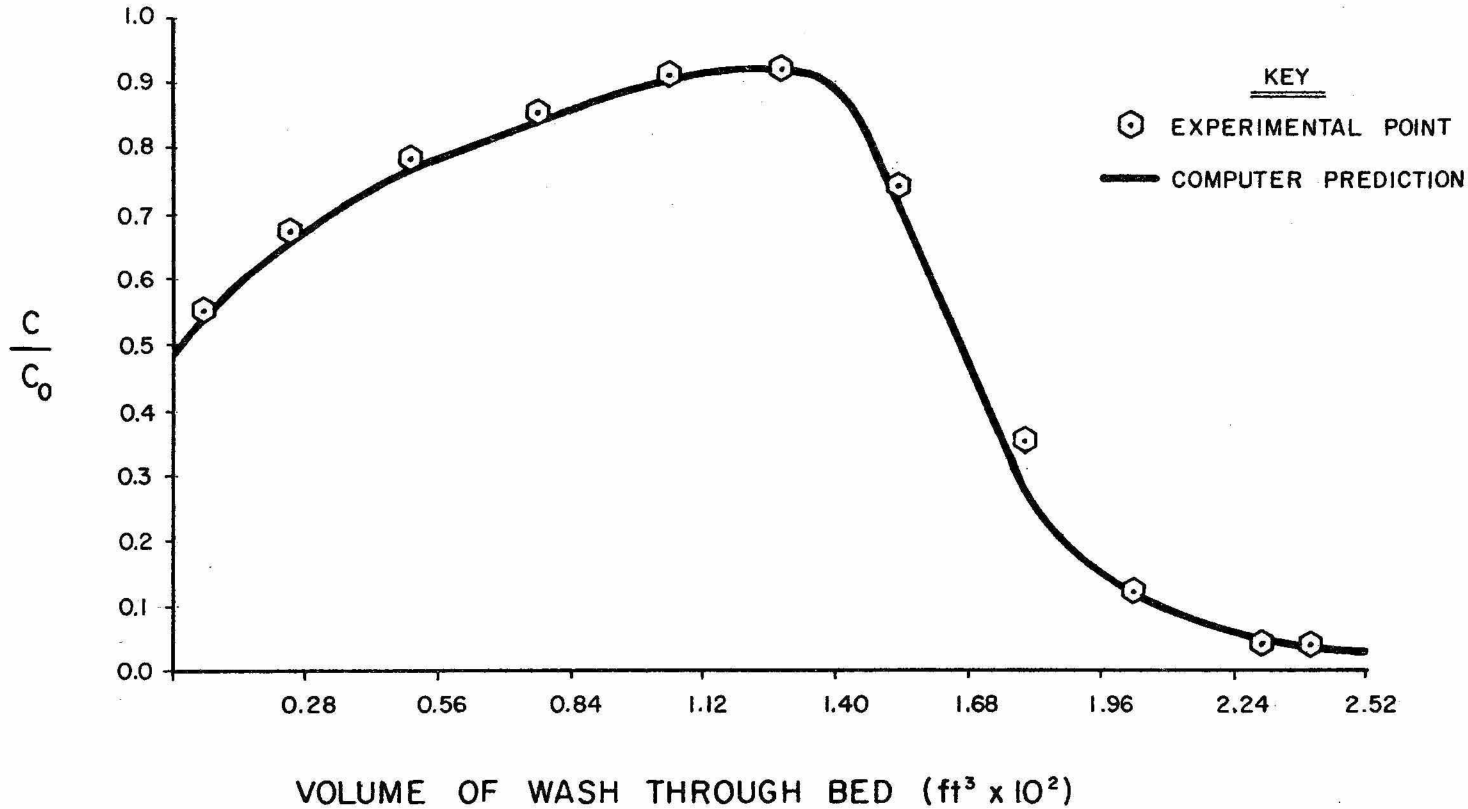

FIGURE 20. UNSATURATED WASH

RUN NO. 1, FLOW RATE—5.10 x 10^{-4} ft^3/sec.

DISCUSSION OF RESULTS

The primary objective of providing the tools and procedures by which wash water could be conserved in industrial filtration operations was realized. Mathematical models describing the washing of a filter cake have been developed for both the unsaturated and the saturated cases. Each of the models was reduced to a computer program with experimentally determined parameters. These parameters were established from experimental data for incompressible cakes (glass beads) and for compressible cakes (alumina hydrate). Use of these computer programs provides the information needed for optimization of filter washing operations.

Saturated Wash

The saturated washing curve combined with a mass balance indicates that essentially 100% of the filtrate is removed from the system. The mass balance was carried out using the initial amount of filtrate in the bed and graphical integration of the washing curve.

It can be seen from the washing curve that there is a period in the wash of direct displacement of the filtrate. This is followed by a period of washing during which the concentration of the filtrate in the effluent stream decreases continuously.

Another important contribution of the saturated washing curve is the determination of the actual, active porosity of the bed. When air is forced through the bed, some of the filtrate remains in the "active" spaces. Therefore, the effluent forced from the bed by the air would not be a true indication of the "active" porosity.

However, the volume of filtrate directly displaced by the wash water is a good indication of the active porosity. This information is valuable in predicting both the unsaturated and partially saturated washing curves.

For the higher flow rates in the saturated washing case, the filtrate concentration in the effluent stream decreases slightly slower after displacement washing ends. This is due to the fact that at the slower flow rates the filtrate has more time to diffuse into the washing stream. This creates a smaller driving force during the latter portion of washing. In other words, there is less filtrate to diffuse into the washing stream.

Unsaturated Wash

The mechanism of the unsaturated washing operation is basically different for an incompressible cake and a compressible cake. Evacuation or draining of the incompressible cake removes relatively large amounts of the filtrate with relatively small amounts remaining in the cake. Since the interstices do not compress and form dead spaces, the filtrate remaining after the evacuation is removed essentially by displacement wash rather than by diffusion from the dead spaces.

Upon drainage or evacuation of the compressible cake, relatively large quantities of filtrate remain not only in the dead spaces (closed channels), but also in the so-called active spaces of the cake. The initial wash water passes through the open active spaces with very little mixing and/or diffusion of the filtrate. Thus, the initial wash water issuing from the cake is of very low concentration.

After the open active spaces have been filled with the wash water, a wash approaching displacement wash is noted. During this period, the outlet concentration rises rapidly and may approach the pure filtrate concentration. This is followed by a period of diffusion wash in which the outlet concentration decreases in much the same manner as in the saturated wash case.

It appears that many of the active channels which were drained or evacuated initially become blind channels. The filtrate in these channels is then removed by diffusion rather than by displacement wash resulting in inefficient use of wash water.

Comparison of Saturated and Unsaturated Wash

For the incompressible filter cake, unsaturated washing provides more efficient use of wash water than does saturated washing. None of the channels become closed as the filtrate is drained or evacuated. Thus the remaining filtrate is removed rather easily by an essentially displacement wash.

For the compressible cake, it was determined that the saturated wash situation was more efficient in reducing the amount of filtrate. It required approximately 1.76×10^{-2} ft^3 of wash water to remove essentially 100% of the filtrate from the bed. In the unsaturated case, it required 2.47×10^{-2} ft^3 of wash water to remove approximately 97% of the filtrate.

Computer Program

Saturated and unsaturated wash curves can be predicted using the respective computer program. The dispersion coefficient, D_t, can be estimated from a plot in Levenspiel (8). The other two parameters, XK and XKD, are determined from the experimental data. The bed height, cross-sectional area, volumetric flow rate, porosity, and active porosity are specified. In addition the "open-active" and "dead-active" porosities are required for the unsaturated case.

For the unsaturated case, the program is initiated after the wash water has penetrated to the bottom of the cake. More work is needed to permit initiation of the program at the instant the wash water is introduced to the top of the cake.

The observed parameters for selected computer runs are given in Table 2. It was determined that for the computer simulation to be stable, a $\Delta t/\Delta z$ ratio of less than fifty should be used.

An attempt was made to determine the relation between the parameters k', k_D(ADEAD), and Reynolds number, Schmidt number and bed porosity. Due to the limited variation in the Schmidt number and bed porosity, the relationship between these two parameters and the dimensionless groups could not be determined. The regression analysis did indicate that $k' = \phi(\varepsilon_{total}, Re^2)$.

Table 2.

Observed Parameters for Selected Computer Runs

Bed Packing	Bed Height (ft)	Flow Rate (ft^3/sec) x 10^4	Filtrate	(XKD) (ADEAD) (k_D, A_D) (mole/sec (moles/ft^3))	XK (k') (sec^{-1})	D_t ft^2/sec
Saturated Wash						
Glass Beads	2	3.52	0.1 N HCl	4.24 x 10^{-5}	0.0227	2.2212 x 10^{-4}
	2	2.35	0.1 N HCl	4.24 x 10^{-5}	0.02	1.999 x 10^{-4}
	2	1.76	0.1 N HCl	4.24 x 10^{-5}	0.0117	1.412 x 10^{-4}
$Al_2O_3 \cdot 3H_2O$	1	6.41	0.065 NaCl	2.12 x 10^{-3}	0.9	7.0 x 10^{-5}
	1	3.44	0.065 NaCl	2.12 x 10^{-3}	0.110	1.907 x 10^{-5}
	1	1.09	0.065 NaCl	2.12 x 10^{-3}	0.02	1.0 x 10^{-5}
Unsaturated Wash						
$Al_2O_3 \cdot 3H_2O$	1	5.11	0.065 NaCl	1.15 x 10^{-3}	0.20	4 x 10^{-5}

APPLICATION OF RESULTS TO INDUSTRIAL OPERATIONS

The results of this investigation may be utilized in industrial operations in the following manner.

A small scale system, similar to the experimental system described earlier, is assembled. The column is packed with the filter material whose washing characteristics are to be determined.

First, the total porosity is determined. This is found by pouring the packing through the filtrate. Filtrate is then drained until the fluid level is even with the top of the packed bed. By determining the volume of filtrate remaining in the bed, the total porosity is determined.

The next step is to perform a saturated washing experiment. The point at which the direct displacement of filtrate stops yields a good approximation of the "active" porosity of the packed filter material. The data obtained from this experiment will be compared to the data obtained from a later unsaturated washing experiment.

The next step in determining the wash characteristics of the filter is to determine the apparent "active" porosity. This step is carried out by packing the bed in a similar manner to the one used in the experimental program of this investigation. After the bed has been packed, the filtrate is forced from the bed by pulling a vacuum on the bed or by applying pressure. The volume of filtrate forced from the bed is then compared to the amount of filtrate directly displaced from the bed during the saturated washing experiment. If the two volumes are essentially the same, the "active" porosity may be determined by the amount of filtrate displaced by air. If the amount of filtrate directly displaced during the saturated washing experiment is greater than the amount of filtrate displaced by the air, it may be assumed that there will be some direct displacement of filtrate in the washing of the drained filter cake.

An experiment employing repetitive steps of saturation followed by evacuation is then performed. After both the saturated washing experiment and the experiment employing evacuation and saturation have been carried out, the amount of water required to lower the filtrate concentration to a specified level may be compared. The more efficient washing method is thus determined.

It should be noted that before each experimental run a new bed of filter packing should be introduced into the experimental apparatus. This will assure obtaining the actual packing properties and flow characteristics of the bed. The method used to measure the filtrate concentration in the effluent stream depends on the filtrate being washed from the filter cake and the equipment available for measuring this concentration.

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The conclusions drawn from this investigation of saturated and unsaturated washing in filters are:

1) The saturated wash condition is more efficient in removing the filtrate in cakes with a fairly high dead porosity. For incompressible cakes where the majority of the void volume is active channels, draining and then washing is more effective than saturated washing.

2) The computer program describing the saturated wash condition will accurately predict the wash curve if the parameters D_t, XKD, and (XKD)(ADEAD) are accurately determined.

3) The active porosity of a bed should be determined by an experiment such as the saturated washing, instead of by evacuation with air.

4) At this time, no good estimation of the area of the dead spaces exposed to the active channels can be obtained.

Based on the results of this investigation it is recommended that:

1) Additional experimental work be done in order to better understand the mechanism of unsaturated washing.

2) Different bed packing and filtrates be studied to determine the relation between the parameters XK and (XKD)(ADEAD) and the Reynolds Number, Schmidt Number and bed porosity.

3) The computer program describing saturated washing be altered to include the concentration gradient in the dead space, instead of using a lumped parameter model.

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NOMENCLATURE

a - area of side channels per ft^3 of bed, ft^2/ft^3

A - cross sectional area of bed, ft^2

ADEAD - cross sectional area of dead spaces, computer symbol for A_D

A_D - cross sectional area of dead space per unit length of bed, ft^2/ft

B - beginning of time increment

c' - concentration of solute, lb solute/ lb solution

c - concentration of filtrate, g solute/ cc solution

C_D - concentration of solute in dead space, lb solute/lb solution

C_{Do} - initial concentration of solute in dead space, lb solute/lb solution

C_o - initial concentration of filtrate, lb solute/ lb solution

D - molecular diffusivity, ft^2/min

D_L - longitudinal dispersion coefficient, cm^2/min

D_t - turbulent dispersion coefficient, ft^2/sec

E - end of time increment

E_o - wash efficiency, %

F - rate of flow of wash, $gal/in^2 min$

J - final distance increment

K.k' - constants

k_D - mass transfer coefficient from dead space, moles/sec $ft^2(mole/ft^3)$

M - molecular weight of solute, lb/lb mole

m - mass, lb.

$\dot{m}$ - source mass flow rate, lb solute/sec ft

n - volume of wash per unit volume of original filtrate

Q - volumetric flow rate, ft^3/sec

R - weight fraction remaining in cake after washing, dimensionless

R' - solute remaining in cake after washing, %

t - time, min, sec

t' - time from initiation of wash, sec

t_D - time of diffusion from dead space, sec

u_{plug} - average velocity, ft/sec

u - average linear velocity, cm/min

V - volume of cake, in^3

V' - volume of cake, ft^3

V_1 - volume of filtrate prior to washing, ft^3

V_w - volume of wash water, ft^3

$(V_f)_i$ - volume of filtrate at start of washing, ft^3

W,W' - weight of soluble material in cake, lb

W_2 - total volume of wash water per volume of filtrate at start, dimensionless

W_2' - value of W_2 for negligible channeling and same viscosity of wash and filtrate

W_6 - constant in equation 6

XKD - mass transfer coefficient from dead spaces, computer symbol for k_D

XK - computer symbol for flow parameter k'

y - weight fraction of filtrate in cake prior to washing, dimensionless

z - distance, ft

Dimensionless numbers

N_{Re} - Reynolds number, dimensionless

N_{Sc} - Schmidt number, dimensionless

Greek symbols

ε - bed porosity, dimensionless

ε_A - active bed porosity, dimensionless

ε_D - dead space porosity, dimensionless

γ,δ - multiplying factors

ρ - density of solution, lb_m/ft^3

ρ_c - density of cake prior to washing, lb/ft^3

ρ_D - density of solution in dead space, lbm/ft^3

ρ_l - density of filtrate in cake, lb/ft^3

θ - time, sec

μ - concentration of filtrate, lb/ft^3