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FINAL REPORT

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WATER RECLAMATION FOR GROUND WATER RECHARGE

PERIOD: JULY, 1971-JUNE, 1972

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WATER RECLAMATION FOR GROUND WATER RECHARGE

D. F. Kincannon and W. G. Tiederman

ABSTRACT

The purpose of this study was to develop solid-liquid separation techniques so that surface waters can be used to effectively recharge a ground water aquifer. Specifically, the research effort centered around (1) the development of an efficient, low pressure drop 2 GPM hydrocyclone, (2) the determination of the appropriate chemical treatment for clay-laden water when hydrocyclones are used, and (3) infiltration studies with a laboratory aquifer. The statistical experimental design techniques did yield a significantly improved hydrocyclone design. Furthermore, the separation performance of the "best" hydrocyclone could be improved from an efficiency of 65 percent to an efficiency of 78 percent when the correct chemical treatment is used. However, it is possible for chemical treatment to actually decrease the removal efficiency. The infiltration studies show that a high degree of separation efficiency is required before clay-laden waters can be used as recharge waters. However, further study is needed before direct application of hydrocyclones is made for recharging aquifers with reclaimed surface waters.

FINAL REPORT

PROJECT A-034-OKLAHOMA

OKLAHOMA WATER RESOURCES RESEARCH INSTITUTE

OKLAHOMA STATE UNIVERSITY

<u>Project Title</u>: Water Reclamation for Ground Water Recharge

<u>Personnel</u>: Co-Principal Investigators:

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<u>Period of Grant</u>: July 1, 1971 to June 30, 1972

I. INTRODUCTION

Water depletion trends in the aquifers of the Oklahoma High Plains area clearly indicate the need for research in methods of water reclamation and artificial ground water recharge.

Artificial recharge is the practice of increasing the amount of water entering a ground water reservoir by some artificial means. Basically there are two methods, injection and infiltration. Injection methods employ what are generally termed "reverse wells" to recharge filtered water directly into the aquifer. Infiltration methods generally utilize water from rivers which may contain a high percentage of suspended solids. This water is caused to enter a porous surface stratum and percolates to the water table. Various combinations and modifications of these methods may be necessary depending on such factors as climate, topography, soil, geology, water quality, purpose of recharge, quantity of water involved, costs, and land use.

For artificial recharge to be practical, the injected water must be able to pass into the aquifer with the least amount of impedance. The efficiency of a project is often reduced by clogging. One of the major causes of clogging is suspended particles in the recharge water. Water reclamation and reuse is an important potential method of augmenting existing water supplies. Reclamation is defined here as the removal of suspended solids and additional chemical treatment to the extent where the water is of suitable quality for all intended uses. In this study, the degree of reclamation was limited to producing a suitable quality water for artificially recharging a ground water aquifer.

A hydrocyclone developed and patented by Oklahoma State University was the chief means for separating suspended solids from the water. The hydrocyclone is a centrifugal separator in which the particulate matter is subjected to accelerations several thousand times gravity. By chemical treatment the efficiency of the hydrocyclone can be enhanced, so that the product water may be suitable for recharge.

The research effort centered around (1) the development of 2 GPM hydrocyclones needed for the solid-liquid separation, (2) the determination of the appropriate chemical treatment for the water when the hydrocyclone is part of the system, and (3) infiltration studies with a laboratory aquifer.

Shortly before the grant period began, the first study, in which OSU designed hydrocyclones were extensively tested as devices for separating naturally occurring clays from water, was completed. The results of this study [1, 2]* clarified the tasks implied by items 1 and 2 above. Specifically, it became apparent that

1. only the open underflow or the contamination trap hydrocyclone configurations would be effective in removing the smaller suspended solids;

2. only coagulants which could form a flocced particle strong enough to withstand the shear stresses in the hydrocyclone would be effective chemical aids in the separation process;

3. economical contamination traps capable of being backflushed would have to be developed before the contamination trap designs would become practical; and

4. since some of the naturally-occurring clays in Western Oklahoma have as much as 73 percent of their weight contributed by particles with diameters less than 5 micrometers, the separators must effectively remove these smaller particles.

Consequently, our efforts in this study concentrated upon the experimental development of more effective open underflow hydrocyclone configurations and the screening of a large number of coagulant aids. In addition, preliminary tests have been conducted with a laboratory aquifer. All testing was conducted with dilute clay slurries which were mixed in the laboratory.

II. MATERIALS AND METHODS

A. GENERAL

The Hydrocyclone

The hydrocyclones used in this study were effectively open-underflow configurations, as shown in Figure 1. A collection pot was used on these devices; however, it was drained at fixed rates which were controlled by a valve. In a few cases the minimum diameter of the conical section, D_u, was sufficiently small that the desired net flow rate through this orifice

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*References cited are included in APPENDIX A.

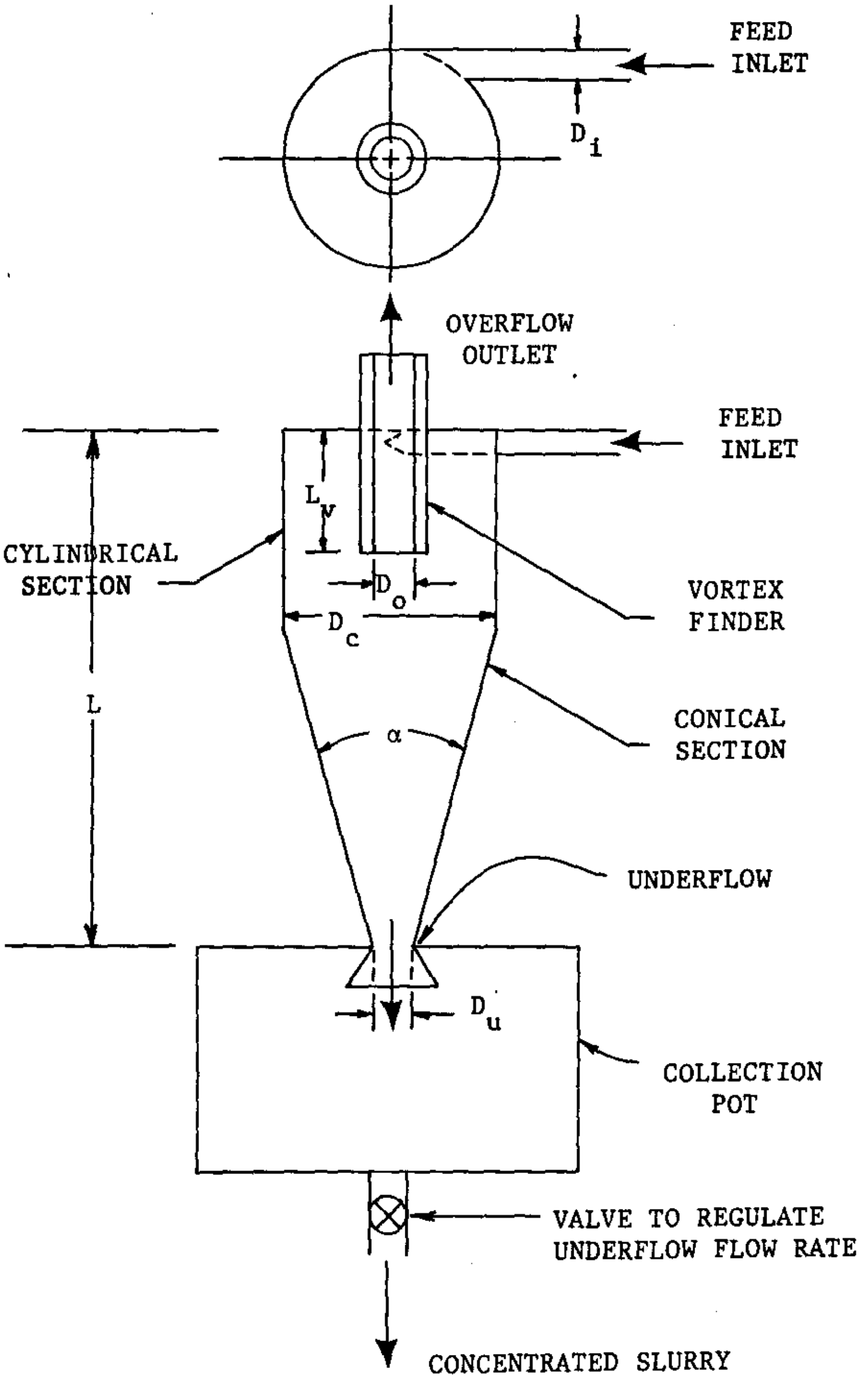


FIGURE 1. HYDROCYCLONE WITH AN OPEN COLLECTION POT

could not be achieved with the collection pot attached. In these cases the collection pot was removed.

Contaminated fluid enters the hydrocyclone through the tangential feed inlet, D_i, at a relatively high velocity (50-100 ft/sec). Since the contaminate has a density greater than the density of the carrier fluid (in this case, water), the contaminate is held near the outer wall as the fluid spirals downward into the conical section of the hydrocyclone. Notice that the outlet for the fluid (the overflow outlet) is centered on the axis of the vessel some distance below the feed inlet. Hence, the rotating fluid is forced to spiral both downwards from the inlet and towards the center in order to escape. Since the rotational motion has an inward radial motion superimposed on it, the solids are subjected to two opposing forces. There is an outward radial force due to the centrifical acceleration and an inward radial force due to the Stoke's drag from the inwardly moving fluid. The magnitude of these forces and, hence, the separation characteristics of the hydrocyclone are dependent upon the physical properties of the contaminate (size, shape, density) as well as the shape of the hydrocyclone.

As the rotating fluid spirals downward toward the minimum diameter of the conical section, the radius of curvature decreases, and the increasing centrifugal forces keep the solids concentrated near the walls. Most of the solids and some of the water continue downward through the minimum diameter of the conical section (the underflow diameter) and into the collection pot. When the underflow diameter does not regulate the amount of flow leaving the collection pot, some of the water which enters the pot must leave the pot along the axis of the separator in an upward return flow called the inner vortex. This inner vortex contains the smaller solid particles which were pulled into the center by the viscous drag forces. Some of these particles are thrown out of the inner vortex before the water leaves the hydrocyclone, but many escape through the overflow outlet. A concentrated slurry is continuously drained from the collection pot via a valve located on the axis of the separator.

Hydrocyclone Test Stands

Two hydrocyclone test stands were constructed and used during the investigation. Both have the characteristics shown in Figure 2. The upstream reservoirs were equipped with mixing paddles so that the dilute clay slurries used to evaluate the hydrocyclone performance could be kept well mixed throughout a test run. Roller pumps were used to pump the slurries from the upstream reservoir through the PVC piping system. Sampling tees and pressure gages were located both upstream and downstream of the hydrocyclone and flow meters were used to measure both the overflow, Q_o, and underflow, Q_u, flow rates. The flow rates were adjusted by a pump by-pass and in some cases by a vari-speed control on the pump motor. The overflow line and the underflow line could also be sampled at their outlets.

Clays

Two different clays were used--Permian Red Clay (PRC) and Roger Mills Gray Clay (RMGC). The PRC is a material of medium plasticity obtained from the Permian marine deposits which are dominant in central Oklahoma. The RMGC is a highly plastic clay obtained from Roger Mills County in western Oklahoma. The size distribution of both clays is given in Table I [3].

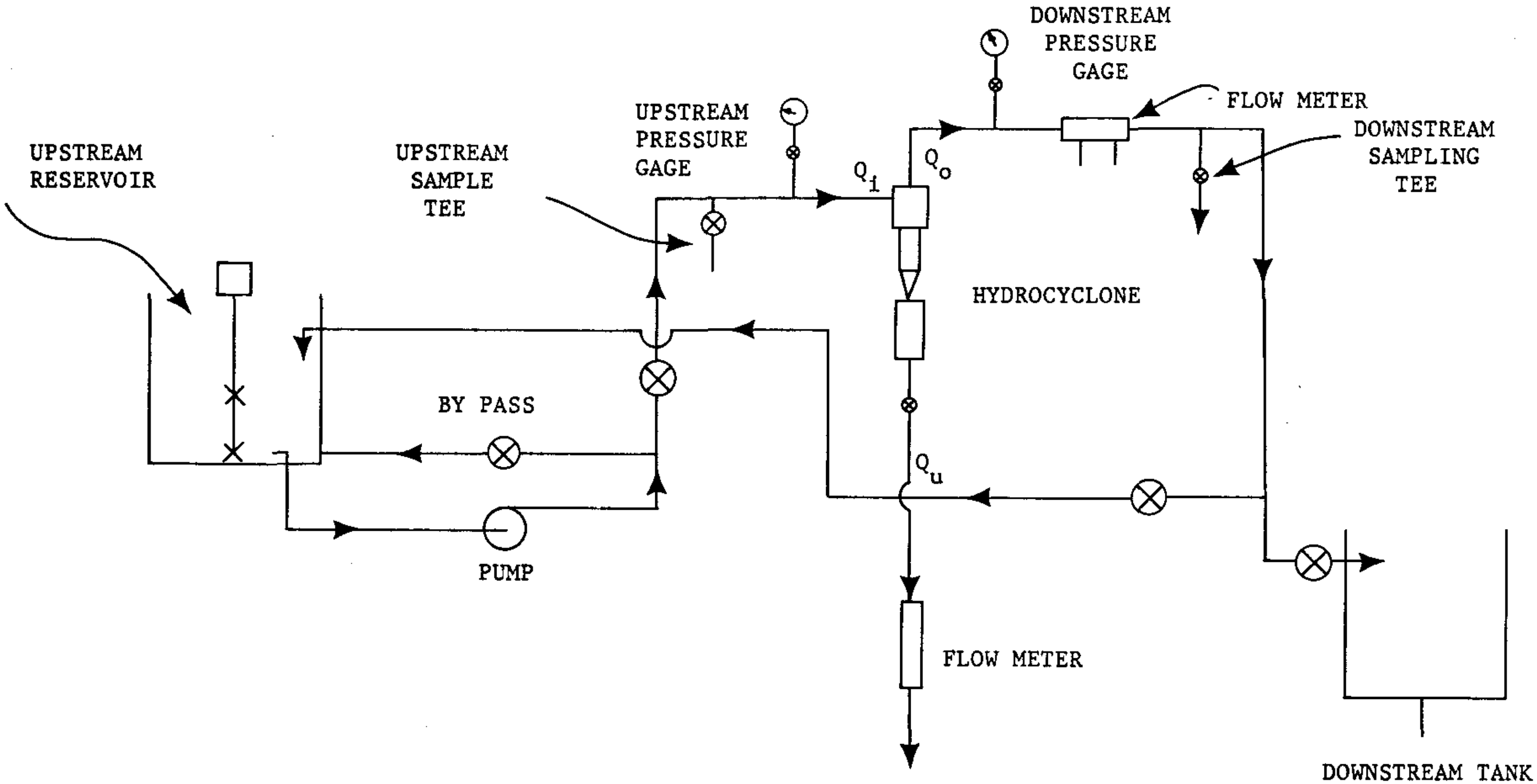


FIGURE 2: SCHEMATIC OF HYDROCYCLONE TEST STANDS

TABLE I. SIZE DISTRIBUTION OF PRC AND RMGC

	PRC	RMGC
Less than 10μ	38%	82%
Less than 5μ	32%	73%
Less than 1μ	26%	2%

Single-Pass Testing of Hydrocyclones

The term "single-pass" is used to describe the testing used to evaluate the hydrocyclones' performance when the test loop was configured so that none of the slurry could be returned to the upstream reservoir during the test run. Hence the clay slurry made a "single pass" through the hydrocyclone. This was accomplished by pumping a fixed volume of well-mixed slurry from the upstream reservoir through the test loop to the downstream catch tank. During the test, samples were withdrawn upstream and downstream of the hydrocyclone from either the sampling tees or the upstream reservoir and the downstream outlet. Samples were also taken in some runs from the concentrated underflow stream. The typical concentration of clay in the upstream tank was 100 mg/liter.

In some instances, the partially clarified slurry caught in the downstream tank was transferred to the upstream reservoir and the single-pass procedure was repeated. Successive single-pass tests conducted in this manner simulate a series of hydrocyclones where the overflow outlet of the first is connected to the inlet of the second, etc. It is important to note that the concentrated underflow stream is discarded in all cases.

Suspended Solids Measurements

The concentration of suspended solids in all the samples were determined using Millipore Corporation filtration equipment. The solids were collected on 0.45μ membrane filters which were dried and weighed according to standard procedures.

Definitions of Efficiency

Two different definitions of efficiency were used during this study to evaluate the hydrocyclone performance. The definition used during the performance testing with coagulant aids is called the separation efficiency, E, and it is defined by

$$E = \frac{I - O}{I}$$

Here I is the gravimetric concentration of solids (mg/l) in the inlet stream and O is the gravimetric concentration of solids (mg/l) in the overflow outlet. A more useful performance index for design purposes is the centrifugal efficiency, E', which is defined by

$$E' = \left(\frac{Q_o}{Q_i}\right) E$$

Here Q_o is volumetric flow rate of the overflow and Q_i is volumetric inlet flow rate. The ratio of flow rates weights the separation efficiency and thereby the centrifugal efficiency is a combined index of the outlet water quality and quantity.

B. HYDROCYCLONE DESIGN

Based upon the suggestions of Bradley [4], Rietema [5], Matschke and Dahlstrom [6], and our own experience, four geometric variables were selected for study in the development of the hydrocyclones. These variables were the inlet diameter, D_i, the outlet diameter, D_o, the maximum conical diameter, D_c, and the total length, L, of the hydrocyclone. By systematically changing these variables in combinations specified by two factorial experimental designs, thirty-two hydrocyclones were designed and the separation performance of thirty-one of these was evaluated.

The rationale for specifying the geometric variables was straightforward. There appears to be reasonable agreement among various investigators about the values of several geometric variables, and where this agreement occurs the accepted values were used. For example, the length of the vortex finder which extends below the inside top of the hydrocyclone, L_v, was maintained at 0.6 D_c. Similarly, the outside diameter of the vortex finder was always 0.5 D_c. Since the amount of underflow was being regulated by a valve on the collection pot, the actual value of the underflow diameter, D_u, was not critical in these designs. Hence, D_u was set at 1/8 D_c. Similarly, the precise value of the included angle of the cone loses much of its importance when an independent variation is made in the total length of the separator. Consequently, the included angle of the cone, α, was 20 degrees.

The geometric variables chosen for study and the range over which they were studied was simply based upon the collective experimental evidence of the referenced investigators. The variables were ones for which conflicting evidence has been reported and the range of variation was chosen to resolve the conflicts. As a result, the two experimental designs include: (1) four levels of D_i/D_c which vary between 1/8 and 1/5, (2) four levels of D_o/D_c which vary from 1/5 to slightly more than 1/3, (3) four levels of L/D_c varying from 4 to 7, and (4) four levels of D_c varying from 9/16" to 1.0". The various combinations which were tested are listed in Table II along with the model number assigned to each design.

During the single-pass experiments used to evaluate these separators, the overflow flow rate was set at 1.8 GPM and the underflow flow rate was nominally adjusted to 0.153 GPM. In some instances, and these are noted on Table III in the Results' section, the underflow flow rate was lower.

TABLE II: GEOMETRY AND MODEL NUMBER OF THE HYDROCYCLONES

Model	D_c	D_i/D_c	D_i	D_o/D_c	D_o	L/D_c	L
1	1.0	0.200	0.200	0.333	0.330	4.0	4.0
2	0.75	0.200	0.150	0.333	0.250	6.0	4.5
3	1.0	0.125	0.125	0.333	0.330	6.0	6.0
4	0.75	0.125	0.094	0.333	0.250	4.0	3.0
5	1.0	0.200	0.200	0.200	0.200	6.0	6.0
6	0.75	0.200	0.150	0.200	0.150	4.0	3.0
7	1.0	0.125	0.125	0.200	0.200	4.0	4.0
8	0.75	0.125	0.094	0.200	0.150	6.0	4.5
9	1.0	0.200	0.200	0.333	0.330	6.0	6.0
10	0.75	0.200	0.150	0.333	0.250	4.0	3.0
11	1.0	0.125	0.125	0.333	0.330	4.0	4.0
12	0.75	0.125	0.094	0.333	0.250	6.0	4.5
13	1.0	0.200	0.200	0.200	0.200	4.0	4.0
14	0.75	0.200	0.150	0.200	0.150	6.0	4.5
15	1.0	0.125	0.125	0.200	0.200	6.0	6.0
16	0.75	0.125	0.094	0.200	0.150	4.0	3.0
110	0.750	0.240	0.180	0.320	0.240	6.0	4.50
111	0.563	0.240	0.135	0.320	0.180	5.0	2.81
112	0.750	0.180	0.135	0.320	0.240	4.0	3.00
113	0.563	0.180	0.101	0.320	0.180	7.0	3.93
114	0.750	0.240	0.180	0.240	0.180	4.0	3.00
115	0.563	0.240	0.135	0.240	0.135	7.0	3.93
116	0.750	0.180	0.135	0.240	0.180	6.0	4.50
117	0.563	0.180	0.101	0.240	0.135	5.0	2.81
119	0.750	0.240	0.180	0.320	0.240	4.0	3.00
120	0.563	0.240	0.135	0.320	0.180	7.0	3.93
121	0.750	0.180	0.135	0.320	0.240	6.0	4.50
122	0.563	0.180	0.101	0.320	0.180	5.0	2.81
123	0.750	0.240	0.180	0.240	0.180	6.0	4.50
124	0.563	0.240	0.135	0.240	0.135	5.0	2.81
125	0.750	0.180	0.135	0.240	0.180	4.0	3.00
126	0.563	0.180	0.101	0.240	0.135	7.0	3.93

All dimensions are in inches.

All of these single-pass experiemnts utilized RMGC which had passed through a 100 mesh screen.

C. CHEMICAL TREATMENT

The objectives of these studies were to determine the effectiveness of various coagulating chemicals and the most effective dosages of these chemicals. The studies were conducted as jar studies and by actual hydrocyclone studies.

The chemicals used in these studies were:

(a) aluminum sulfate

(b) lime

(c) ferric sultate

(d) organic polyelectrolytes

The clay used in these studies was Permian Red Clay (PRC) as described in Table I.

Jar Studies

The jar studies were conducted with a Phipps and Bird, Inc., laboratory stirrer. Six 500 ml samples were placed on the stirring apparatus. The desired dosage of chemicals were added to each sample under rapid mix conditions. All chemicals except the polymer were added at time zero; the polymer was added after two minutes of rapid mixing. Rapid mixing was continued for one minute after adding the polymer and then a slow mix was maintained for 17 minutes. The rapid mix was at 100 RPM and the slow mix was at 20 RPM.

The suspended floc was allowed to settle and samples were collected for optical density measurements.

Hydrocyclone Studies

The hydrocyclone used in these studies was model #2 installed in an open underflow configuration as shown in Figure 2. The hydrocyclone was operated at a flow rate of 2.0 GPM with an underflow of 5 percent of the inflow rate.

The required amount of PRC to give a concentration of 100 mg/l was added to the holding tank. The desired chemical dosage was then added and the system was allowed to flocculate before being pumped through the hydrocyclone. Samples were taken in the reservoir, at the outlet of the reservoir (before the pump), after the pump, and after the hydrocyclone in both the overflow and the underflow. Sampling consisted of taking a small amount of the flowing liquid, at each sampling place, several times during the runs. These samples were composited and a 50 ml sample was taken for suspended solids measurement.

D. RECHARGE STUDIES

The apparatus used in this study consisted of an ordinary constant head permeameter as shown in Figure 3, where h is the head of water above the evaporating dish and X is the length of the soil column. A large Pyrex battery jar was used to contain the turbid water mix which was conveyed to the constant head permeameter by siphoning. The turbid water mix was constantly stirred throughout each experimental run. The turbid waters were obtained by mixing Permian Red Clay (PRC) with tap water. Concentrations of 316 mg/l, 143 mg/l, and 70 mg/l were percolated through the porous media [7].

The porous media consisted of Ottawa (silica) sand having an effective diameter of 0.12 mm and a uniformity coefficient of 1.5. The sand was placed in the plastic permeameter cylinder with the sand column being

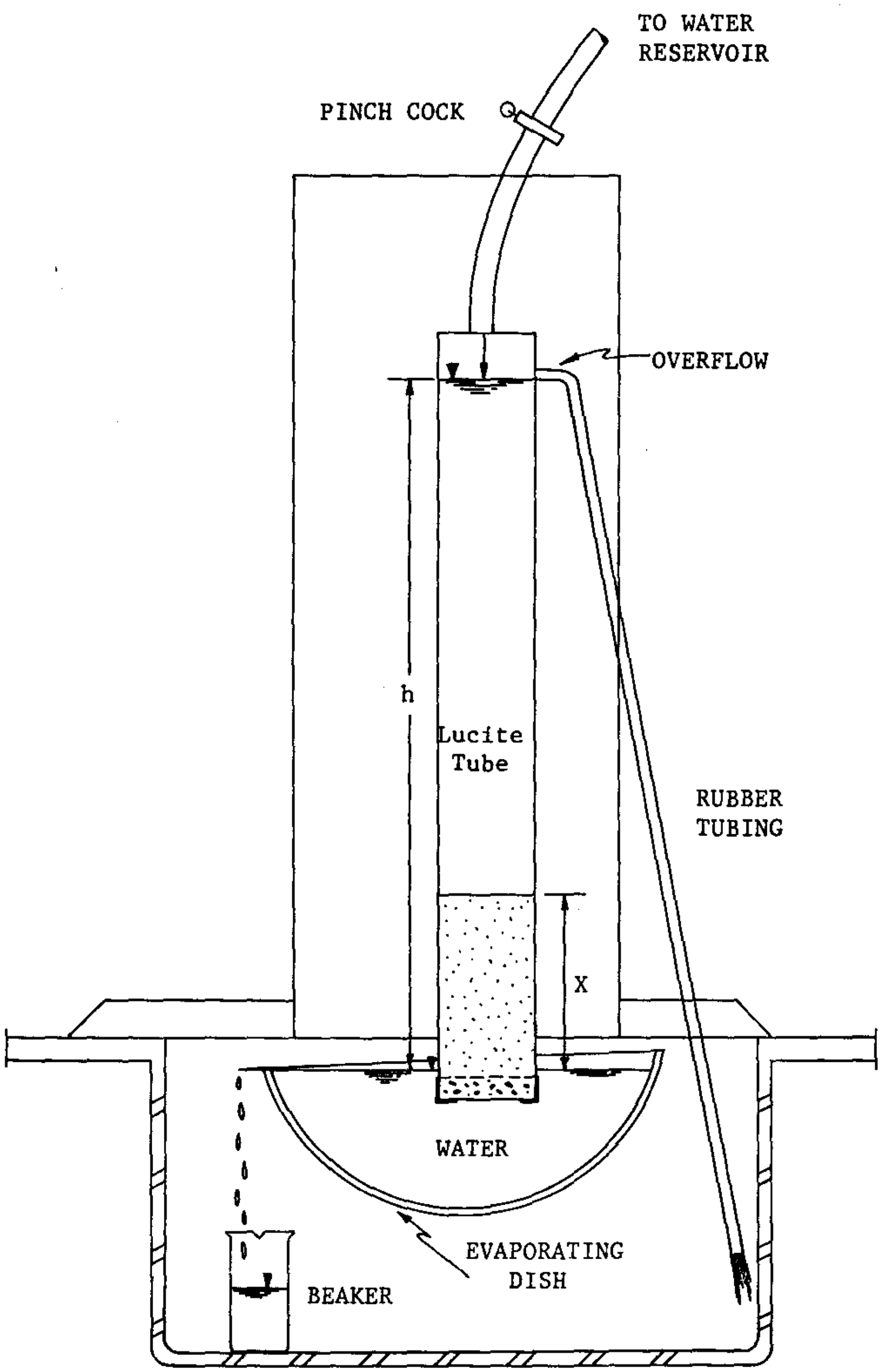


FIGURE 3. DIAGRAM OF A PERMEAMETER

20 centimeters long and having a surface area of 19.63 square centimeters. Initial permeability through the sand column, using clear water, was 6.9×10^{-2} cm per second.

Measurements of the reduction in infiltration rate were taken in the following manner: A 600 ml beaker was placed beneath the outfall from the evaporating dish. Readings were taken for up to 26 hours in the 70 mg/l turbid water. Readings at 16 hours were conclusive for the 143 and 316 mg/l concentrations. Each reading was taken for a duration of 120 seconds and the flow recorded in cubic centimeters.

III. RESULTS

A. HYDROCYCLONE DESIGN

Table III and Figure 4 summarize the effects of geometric variation upon the pressure drop (power consumption) and the centrifugal efficiency of the 2 GPM hydrocyclones. As shown quite graphically in Figure 4, the most effective and the most economical to operate separator is model number 2. This unit has a centrifugal efficiency of 55.3 percent on RMGC at a pressure drop of 29 psi. While similar efficiencies were achieved with models 7, 115, and 122, their pressure drops were respectively 63, 86, and 111 psi.

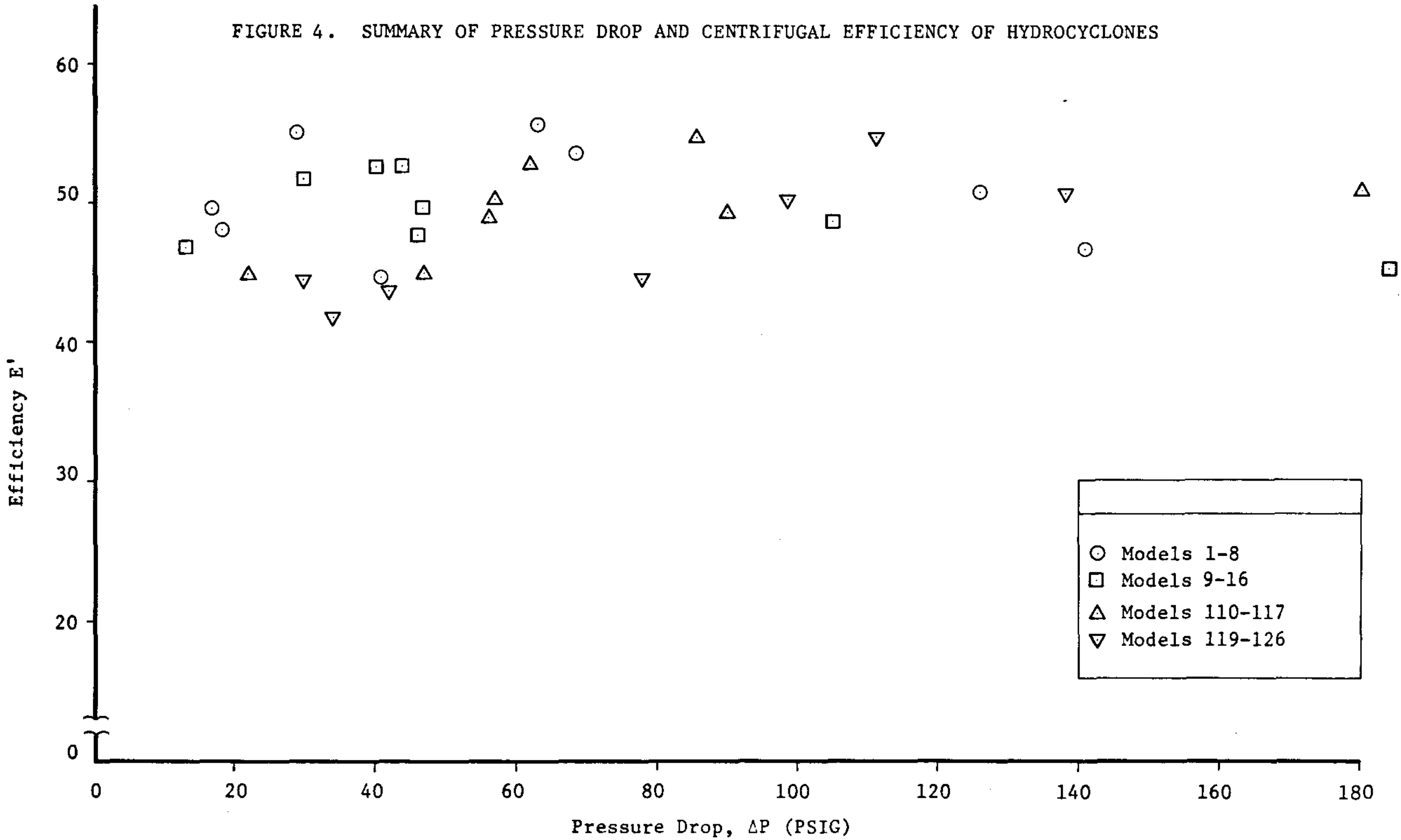
The most comprehensive way to analyze the data is to perform a multiple regression analysis. For this purpose the normalized variables, X_i, are introduced in Table III. The center point and the normalization for these variables were chosen from the original factorial design which is composed of models 1 through 16. X_1 is the normalized variation in D_c; X_2 corresponds to the ratio of D_i/D_c; X_3 corresponds to D_o/D_c; and X_4 is the normalized variation in L/D_c. By performing a multiple regression analysis to generate a response surface and then by searching for optimum values of this surface

TABLE III: SUMMARY OF THE CENTRIFUGAL EFFICIENCY AND PRESSURE DROP OF THE 2 GPM HYDROCYCLONE

Model	X_1	X_2	X_3	X_4	E' (%)	ΔP (psi)	% Q_u (GPM)
1	1.0	1.0	1.0	-1.0	49.03*	17.1*	7.85
2	-1.0	1.0	1.0	1.0	55.3*	29.2*	7.85
3	1.0	-1.0	1.0	1.0	44.3	40.5	7.85
4	-1.0	-1.0	1.0	-1.0	50.3	126.0	7.85
5	1.0	1.0	-1.0	1.0	48.0	19.0	7.85
6	-1.0	1.0	-1.0	-1.0	53.8	69.5	7.85
7	1.0	-1.0	-1.0	-1.0	55.6	63.0	7.85
8	-1.0	-1.0	-1.0	1.0	46.6	141.0	7.85
9	1.0	1.0	1.0	1.0	46.6	13.0	7.85
10	-1.0	1.0	1.0	-1.0	52.2*	40.0*	7.85
11	1.0	-1.0	1.0	-1.0	52.3	44.0	7.85
12	-1.0	-1.0	1.0	1.0	48.4	105.5	7.85
13	1.0	1.0	-1.0	-1.0	51.4*	30.5*	7.85
14	-1.0	1.0	-1.0	1.0	49.6	46.5	7.85
15	1.0	-1.0	-1.0	1.0	46.6	47.5	7.85
16	-1.0	-1.0	-1.0	-1.0	45.2	185.0	6.57
110	-1.0	2.08	0.810	-1.0	44.7	22.0	7.85
111	-2.5	2.08	0.810	1.0	52.7	62.0	3.55
112	-1.0	0.46	0.810	0.0	50.9*	57.0*	7.85
113	-2.5	0.46	0.810	1.0	49.3	90.0	5.86
114	-1.0	2.08	-0.378	2.0	44.9	47.0	7.85
115	-2.5	2.08	-0.378	1.0	54.7	86.0	7.85
116	-1.0	0.46	-0.378	2.0	49.0	56.0	7.85
117	-2.5	0.46	-0.378	-1.0	50.7	180.0	6.31
119	-1.0	2.08	0.810	0.0	44.1	30.0	7.85
120	-2.5	2.08	0.810	-1.0	--	--	--
121	-1.0	0.46	0.810	1.0	43.5	42.0	7.85
122	-2.5	0.46	0.810	0.0	54.5	111.0	3.42
123	-1.0	2.08	-0.378	-1.0	41.9	34.0	7.85
124	-2.5	2.08	-0.378	0.0	50.4*	99.5*	7.37
125	-1.0	0.46	-0.378	-1.0	44.4	78.0	7.85
126	-2.5	0.46	-0.378	2.0	50.2*	138.0*	7.37

*Average of multiple runs

FIGURE 4. SUMMARY OF PRESSURE DROP AND CENTRIFUGAL EFFICIENCY OF HYDROCYCLONES



potentially better hydrocyclones could be designed. However, it is unlikely that the improvements which could be achieved would raise the centrifugal efficiency substantially above that of model 2. The regression analysis and optimization search were part of the work proposed for the second year of this project.

Pressure drop correlations for models 1 through 16 were developed using graphical techniques [8]. These relationships are:

$$\Delta P = \left[\frac{Q_i \, D_c^{0.425}}{3.39 \, D_i^{1.329} \, D_o^{0.625} \, L^{0.43}}\right]^2$$

when $D_o > D_i$ and

$$\Delta P = \left[\frac{Q_i \, D_c^{0.425}}{3.06 \, D_i^{1.035} \, D_o^{0.625} \, L^{0.43}}\right]^2$$

when D_o is approximately equal to D_i. In using these correlations ΔP must have the units of psi, D_i, D_o, D_c, and L must be expressed in inches and Q_i must have the units of GPM.

B. CHEMICAL TREATMENT

Jar Studies

The results of the jar studies are shown in Table IV. It can be seen that a wide range of responses to various chemical treatment was observed. The coagulant aids PR-10 and PR-11 were unsatisfactory in coagulating PRC.

These results provided the basis for chemical treatment in the hydrocyclone studies.

TABLE IV: RESULTS OF JAR STUDIES

Polyelectrolyte mg/l	Alum mg/l	Lime mg/l	Ferric mg/l	Percent light transmittance after 20 minutes
Calgon 2630				
-	--	--	--	77
-	20	--	--	90
2	40	--	--	95
2	60	10	--	97
2	70	20	--	96
2	80	30	--	98
Calgon 2690				
1	--	--	--	89
1	20	--	--	95
1	20	20	--	94
1	20	10	--	92
1	--	10	--	89
1	40	20	--	98
Calgon 2700				
0.2	--	--	--	81
0.2	--	5	--	81
0.12	30	--	--	96
0.12	10	20	--	88
0.12	20	5	--	96
0.12	40	10	--	88
Calgon 2660				
4	30	--	--	80
8	--	--	15	79
8	20	--	10	78
6	40	--	10	80
6	20	--	20	83
8	40	--	20	79
Calgon 2570				
2	20	10	--	87
2	20	20	--	86
2	20	10	10	87
2	20	20	30	94
2	20	--	20	90
2	20	--	10	89

TABLE IV--CONTINUED

Polyelectrolyte mg/l	Alum mg/l	Lime mg/l	Ferric mg/l	Percent light transmittance after 20 minutes
Calgon 2870				
-	80	20	10	79
2	40	20	10	96
2	20	20	10	94
2	20	30	20	95
2	20	10	20	79
2	20	20	20	89
Calgon 2900				
0.8	20	30	10	95
0.8	20	20	20	95
0.8	20	10	30	97
0.8	20	30	10	94
0.8	20	20	20	96
0.8	20	10	30	97
Calgon 3000				
0.8	20	10	30	91
0.8	20	20	20	96
0.8	20	30	10	93
0.8	20	10	10	88
0.8	20	20	20	94
0.8	20	30	--	82
Accofloc 350				
20	20	20	30	99
20	20	30	10	94
20	20	30	20	95
20	20	10	30	100
20	20	20	10	94
20	20	30	15	93
Accofloc 352				
1 ml	20	--	50	97
1 ml	20	10	40	99
1 ml	20	20	30	99
1 ml	20	30	20	96
1 ml	20	40	10	95
1 ml	20	50	--	87

TABLE IV--CONTINUED

Polyelectrolyte mg/l	Alum mg/l	Lime mg/l	Ferric mg/l	Percent light transmittance after 20 minutes
PR-10				
1 ml	--	--	20	82
1 ml	--	10	10	90
1 ml	20	30	30	93
1 ml	20	30	10	92
1 ml	20	50	20	91
1 ml	20	50	10	91
PR-11				
1 ml	20	50	10	81
1 ml	20	40	30	87
1 ml	20	30	20	89
1 ml	20	20	10	81
1 ml	20	10	30	73
1 ml	20	--	20	75

Hydrocyclone Studies

a. Single Pass Studies

The results of the single pass hydrocyclone studies are shown in Table V. It can be seen that with no chemical treatment a removal efficiency of 65 percent was obtained with the hydrocyclone. It can also be seen that chemical treatment provided a wide range of responses. In some cases the chemical treatment actually decreased the removal efficiency. The best removal efficiency was obtained with a chemical treatment of 1.0 mg/1 Calgon 2690, 10 mg/1 alum, and 10 mg/1 ferric sulfate. This removal efficiency was 78.2 percent. This provided a water with only 21.8 mg/1 of suspended solids.

b. Multiple Single Pass Studies

The results of multiple single pass studies are shown in Figures 5 to 9 . These figures show the suspended solids concentration in both the effluent and underflow of the hydrocyclone after each of the three passes. It can be seen that very little removal of suspended solids was achieved after the first pass. It can also be seen that the suspended solids concentration in the underflow decreases very rapidly after the first pass. However, the underflow concentration never decreases to that of the effluent, thus, showing that some concentration and removal of the suspended solids is still taking place during the second and third pass.

c. Recharge Studies

The results of permeability tests involving percolation of a turbid water of PRC through a porous media are shown in Figure 10. It can be seen that the permeability decreased very rapidly for a water containing 316 mg/1 PRC; whereas, the permeability decreased at a much slower rate for waters

TABLE V: RESULTS OF SINGLE PASS STUDIES

Chemical Treatment			Separation Efficiency	Final Effluent Suspended Solids	Underflow
Polyelectrolyte mg/l	Alum mg/l	Iron Salts mg/l	%	mg/l	SS
--	--	--	65	35	605
Calgon 2600					
1	10	5	50	50	858
1	20	5	27.2	72.8	800
2	30	10	48	52	770
Calgon 2660					
5	30	--	54	46	633
15	30	20	66	34	722
Calgon 2870					
5	30	30	50	50	754
5	50	20	23	77	905
Calgon 3000					
0.4	20	--	20	80	800
1.2	30	10	22.2	77.8	915
2.0	30	30	63.8	36.2	1138
Calgon 2900					
1.8	30	30	48.3	52.7	930
1.5	20	30	21	79	945
0.8	20	20	4	96	785
Calgon 2700					
1.0	30	30	36	64	1032
Calgon 2690					
1.0	10	10	78.2	21.8	906
2.0	10	20	68.4	31.6	622
3.0	30	50	46.0	54	1300
Calgon 2630					
3	30	30	45.2	54.8	1046
5	50	50	30	70	961
1	10	15	56.6	43.4	648
Calgon 2630 1.0 Calgon 2690 1.0	10	10	52	48	880
Calgon 2630 1.5 Calgon 2690 1.5	10	10	50	50	841
Acofloc 350					
20	20	20	21	79	--
---	40	40	20	80	826

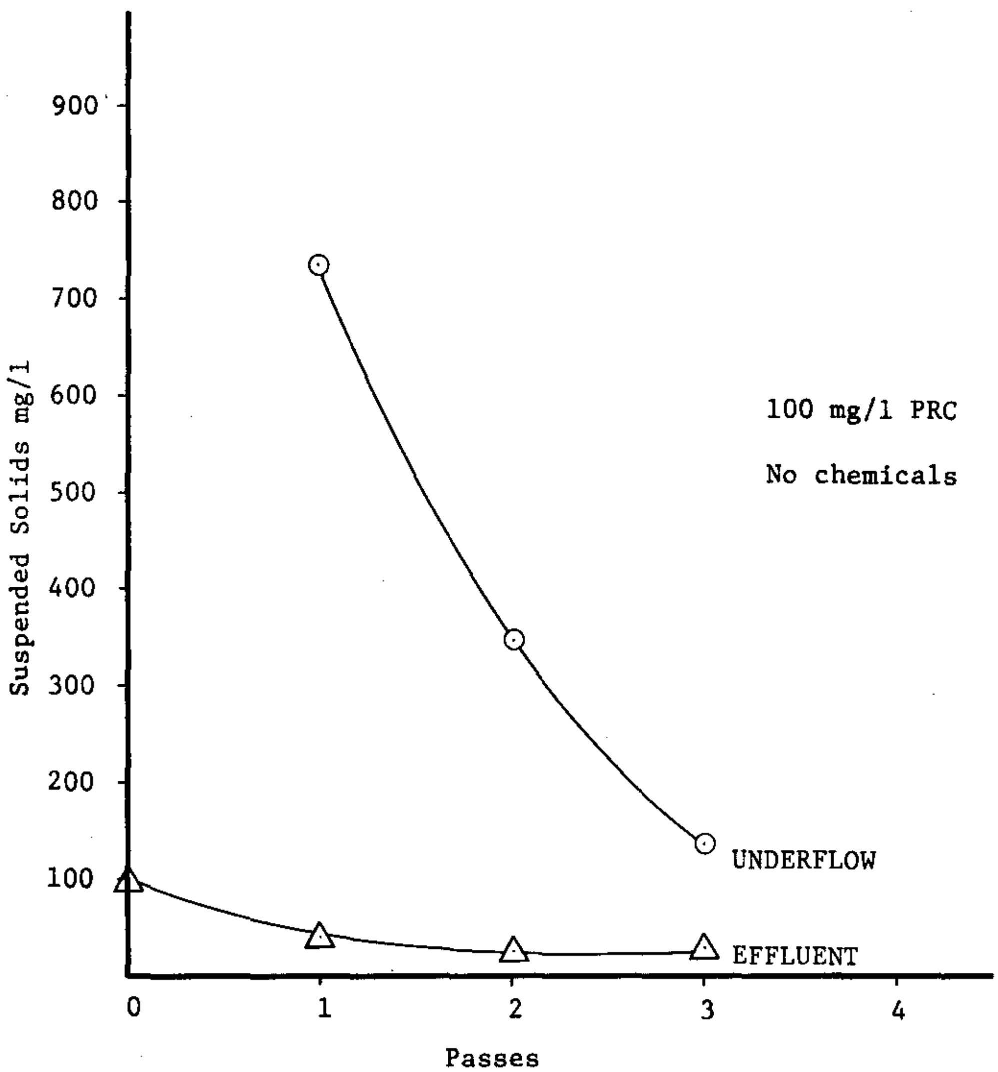


FIGURE 5. MULTIPLE SINGLE PASS STUDIES FOR NO CHEMICAL TREATMENT

FIGURE 6. MULTIPLE SINGLE PASS STUDIES FOR CHEMICAL TREATMENT AS SHOWN

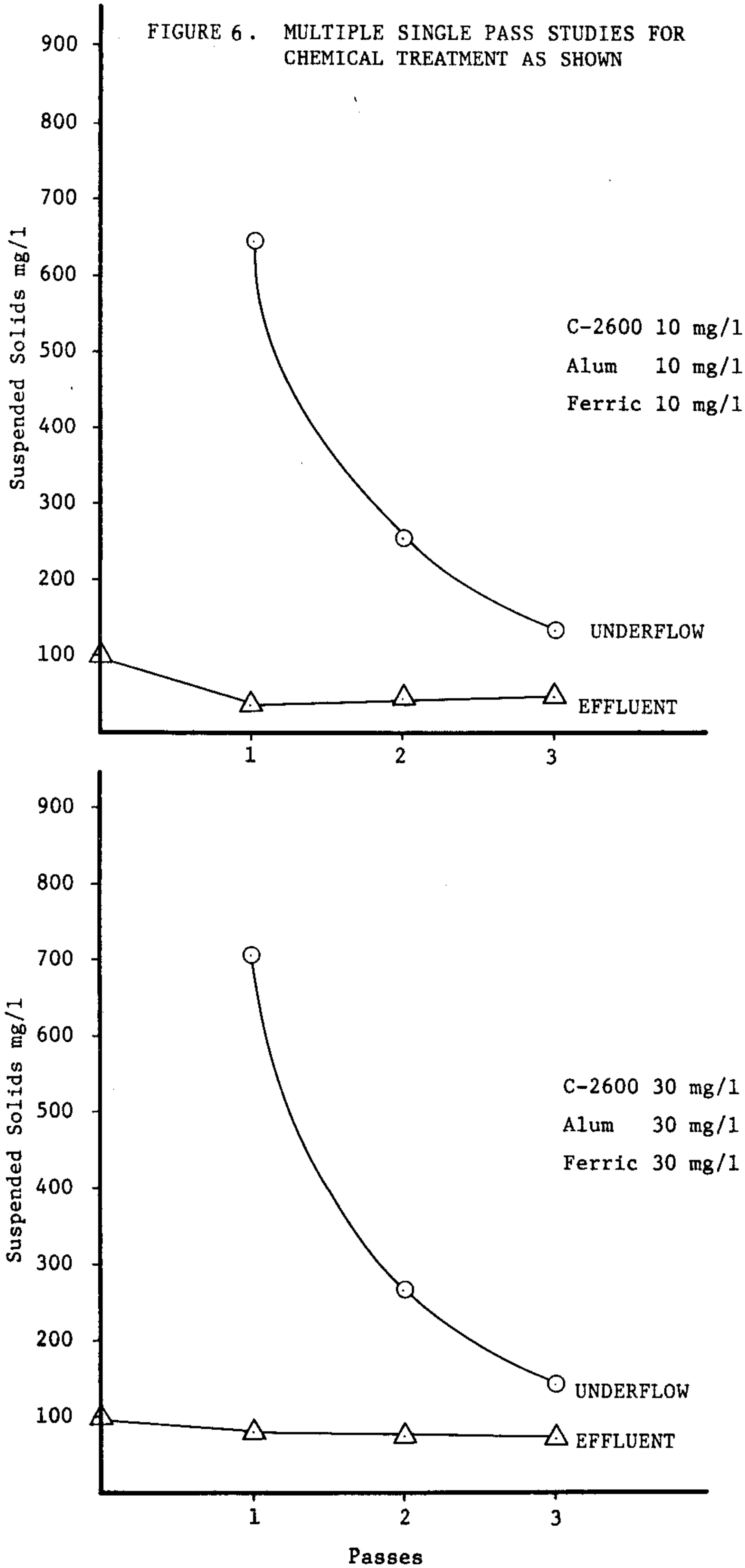


FIGURE 7. MULTIPLE SINGLE PASS STUDIES FOR CHEMICAL TREATMENT AS SHOWN

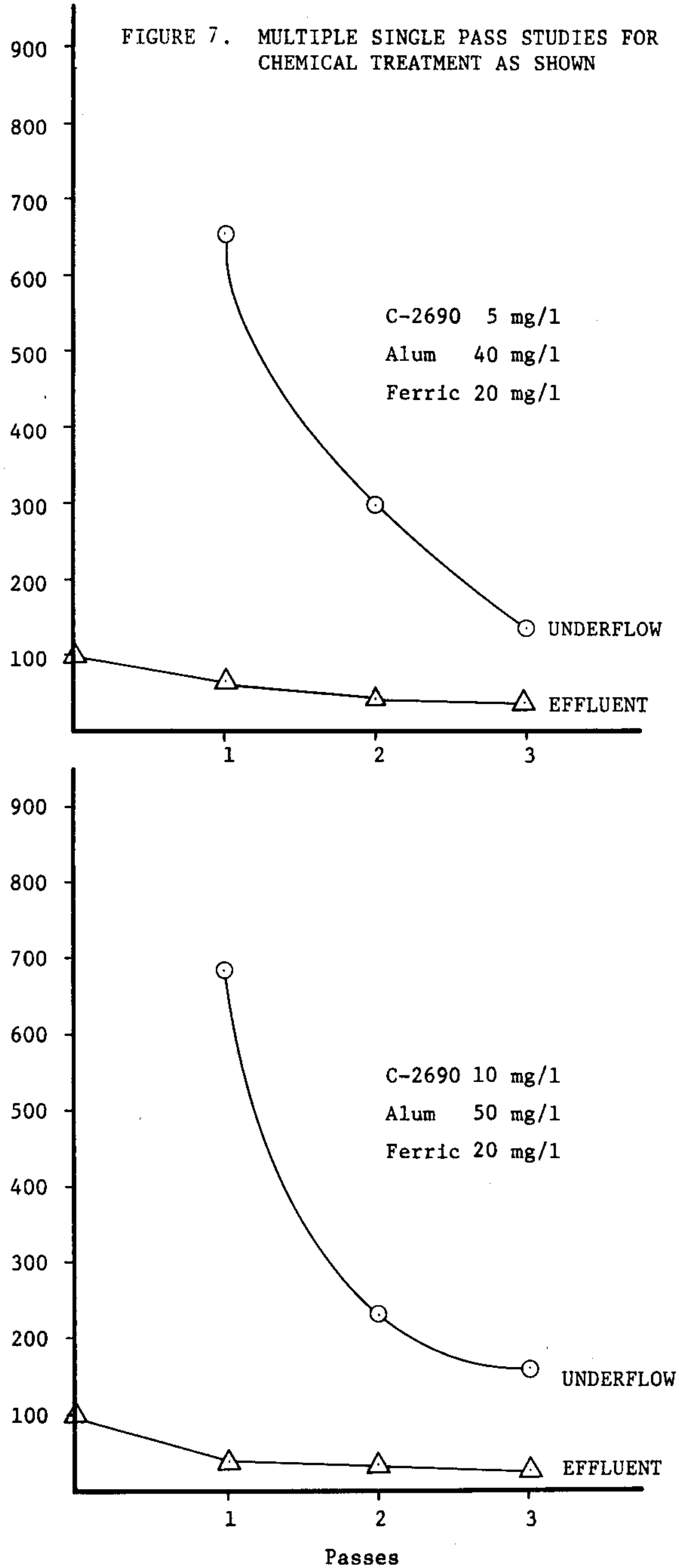


FIGURE 8. MULTIPLE SINGLE PASS STUDIES FOR CHEMICAL TREATMENT AS SHOWN

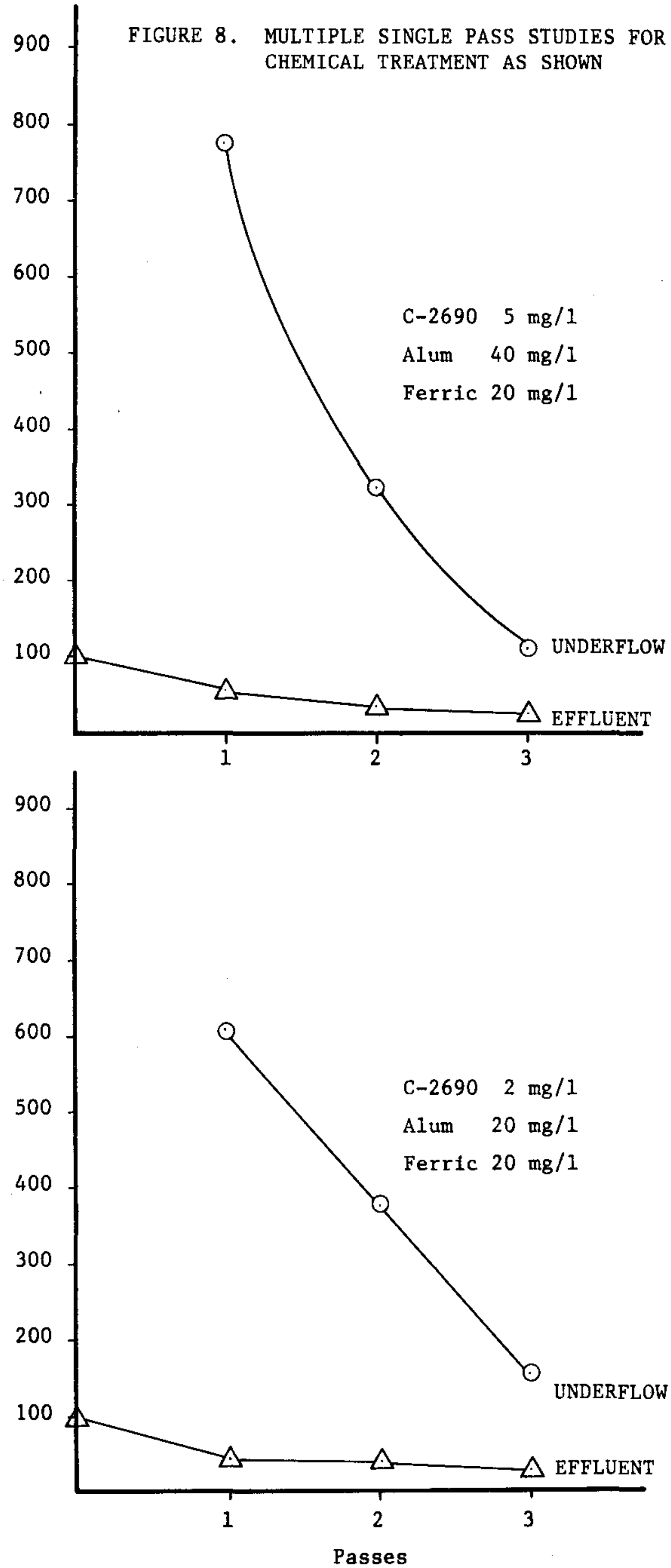
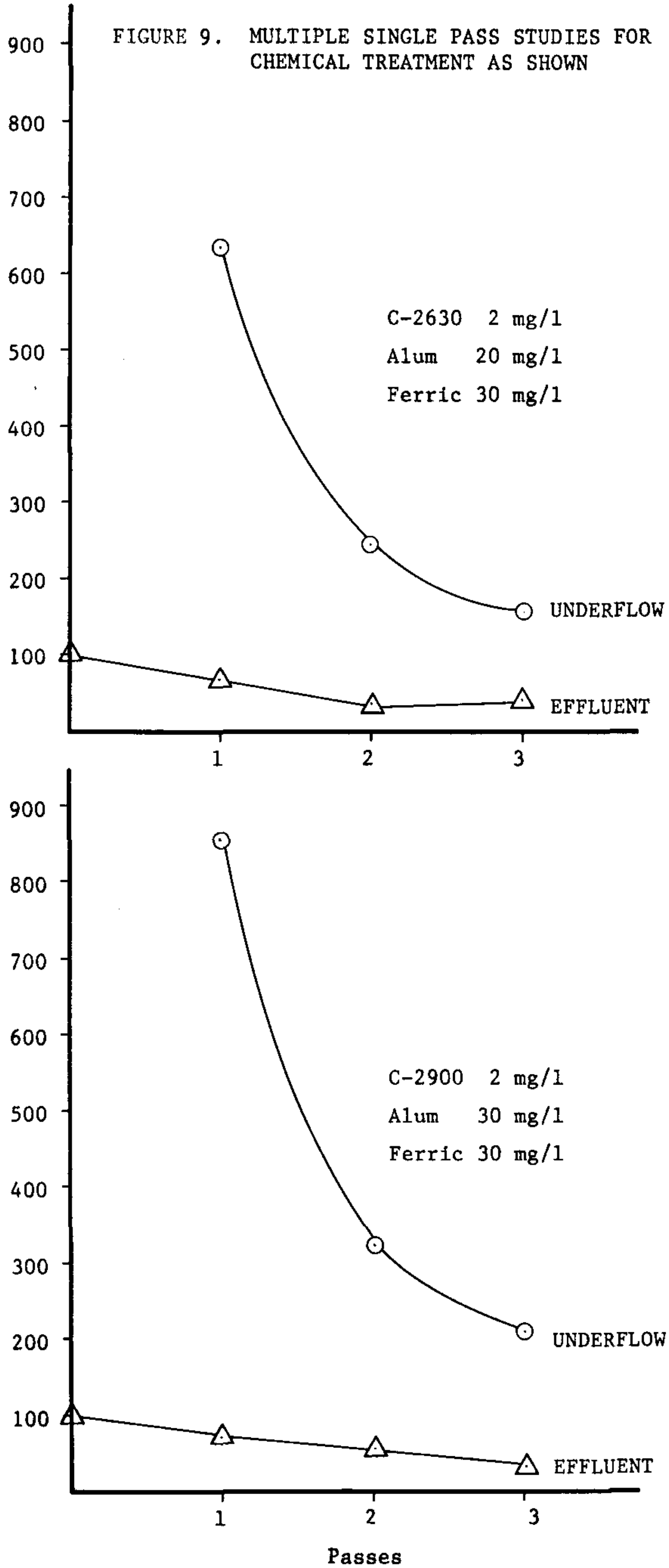


FIGURE 9. MULTIPLE SINGLE PASS STUDIES FOR CHEMICAL TREATMENT AS SHOWN



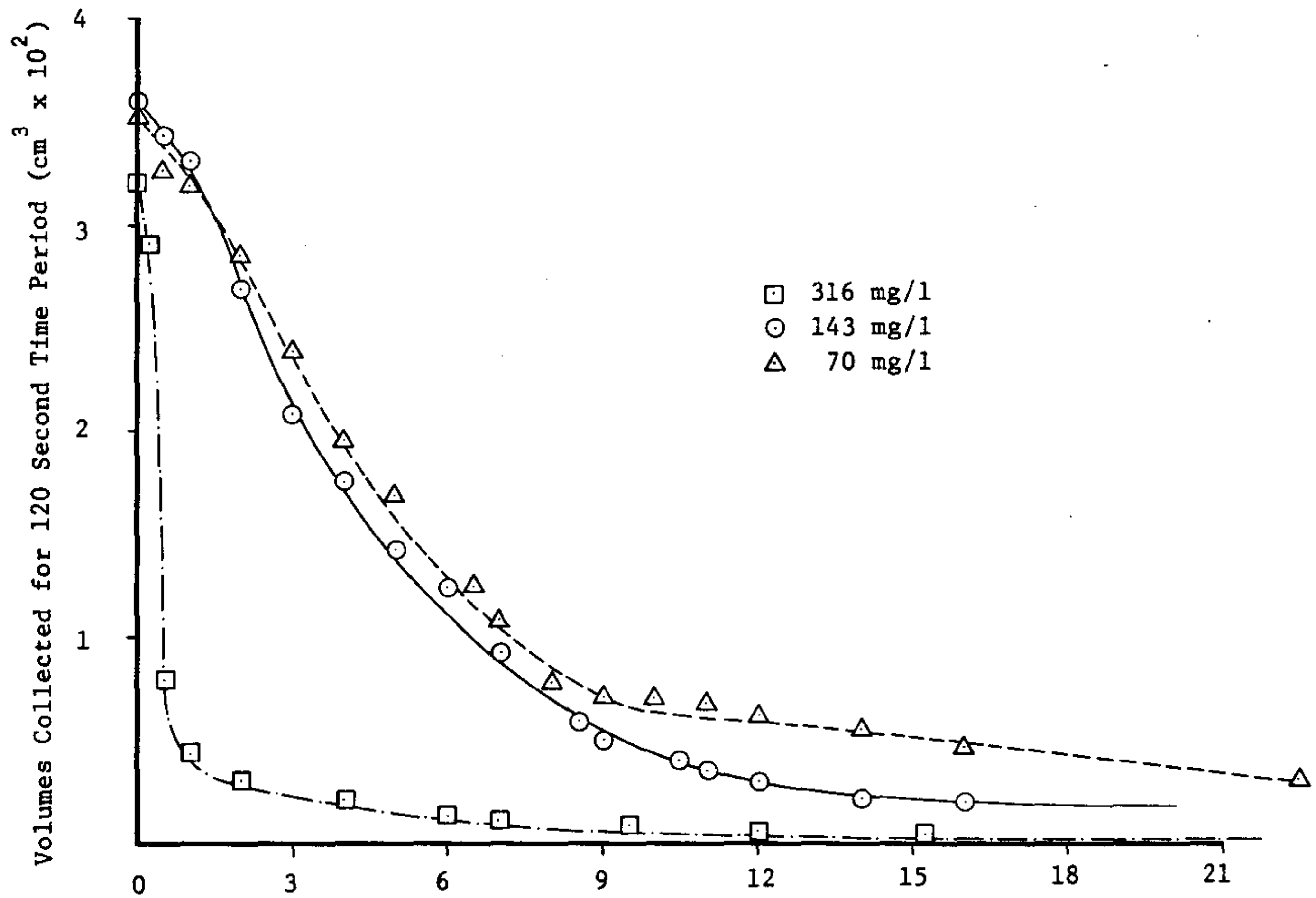


FIGURE 10. VOLUMES COLLECTED FOR 120 SECOND TIME PERIOD VERSUS ELAPSED TIME

containing 143 mg/l and 70 mg/l PRC. It is interesting to note that even though there was a two fold difference in concentrations for the two lowest concentrations, the change in permeability for the two was essentially the same.

Figure 11 shows the total volume of flow accumulated at various time intervals. This shows how clogging is related to solids concentrations and the relative amounts of water that can be infiltrated through the soil in a given time. Both the 143 mg/l and the 70 mg/l waters follow the same path closely until later in the run when the 143 mg/l water begins to exhibit a smaller accumulated flow. The 316 mg/l curve is drastically different from the other two showing a marked decrease in total accumulated volume.

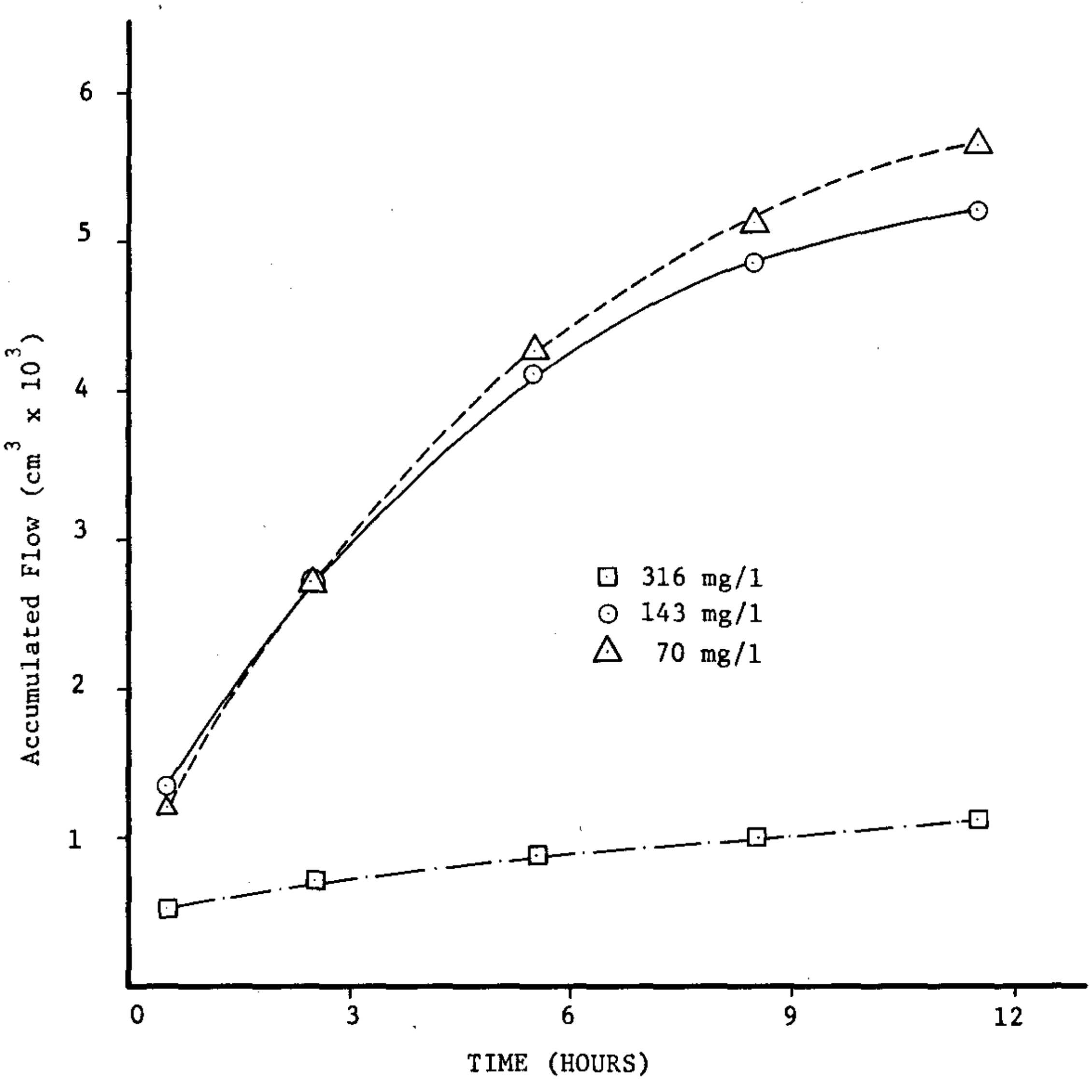


FIGURE 11. ACCUMULATED FLOWS VERSUS ELAPSED TIME

IV. DISCUSSION AND CONCLUSIONS

Substantial progress was accomplished during the program in the development of open-underflow hydrocyclones. For example, the 2 GPM hydrocyclone used by Cobb [1, 2] had a centrifugal efficiency of 37 percent on RMGC and a pressure drop of 130 psi at the rated flow. Model number 2 developed in this study had a centrifugal efficiency of 55 percent on RMGC and a pressure drop of 29 psi at the rated flow. It should be especially noted that this significant improvement in separation performance was accomplished along with a reduction in the pressure drop and hence power requirement. As pointed out in Section III it is not yet clear that model number 2 is the best possible geometric configuration. However, it is extremely unlikely that further significant improvements in performance can be made.

A wide variation of chemical coagulating agents were studied. This study has shown that high shear resistant coagulating agents can improve the operation of the hydrocyclone. However, care must be exercised in selecting the coagulating chemicals. It was observed that several of the coagulating chemicals actually decreased the efficiency of the hydrocyclone.

The laboratory recharge studies [7] led to the following conclusions applicable to the percolation of water containing various amounts of PRC into Ottawa silica sand:

1. Clogging of a soil during infiltration by water containing suspended clay particles is basically a surface sealing process.
2. After a horizontally continuous surface layer is formed, clogging progresses at approximately the same rate for varying concentrations of suspended matter. Although clogging and infiltration loss may progress at the same rate, the accumulated infiltration is, of course, much lower.

3. Clay particles were observed to penetrate deep into the sand column, but it can be concluded that this deep penetration has no effect on the overall infiltration rate.

4. Low concentrations of suspended matter will eventually reduce the infiltration rate, but the rate will never completely reach zero. Total removal of particulate matter would need to be approximated by the hydrocyclone in order to solve the problem of clogging by suspended solids.

Thus the preliminary recharge studies showed that when PRC is the solid contaminate in surface water, that a high degree of separation efficiency is required before the water can be effectively used as a recharge water. Studies using hydrocyclone clarified water and an Ogallala sand aquifer were planned for the second year of the project. Since the project was terminated at the end of the first year, these studies have not been conducted and it is not possible to reach any reliable conclusions about the practical applicability of the concept for the Oklahoma Panhandle.

APPENDIX A: REFERENCES

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