IRON REMOVAL FROM WATER SUPPLIES

(Thesis No. 189)

by

Veera Vitayaudom

SEATO Graduate School of Engineering
Bangkok, Thailand
1967

IRON REMOVAL FROM WATER SUPPLIES

Thesis by

Veera Vitayaudom

For the Degree of Master of Engineering

SEATO Graduate School of Engineering
Bangkok, Thailand
1967

IRON REMOVAL FROM WATER SUPPLIES

by

Veera Vitayaudom

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Engineering in the SEATO Graduate School of Engineering, Bangkok, Thailand.

Approved by: .... 10 Aug 67

Dr. Surin Sethamanit
Special Lecturer in Public
Health Engineering

Accepted by: .... 10 Aug. 1967....

Milton E. Bender, Jr.
Dean

ACKNOWLEDGEMENTS

The writer wishes to express his profound gratitude to Dr. R.T. Skrinde for his guidance and suggestions during the course of experiments, to Dr. Surin Setamanit and Prof. M.B. Pescod for their constructive criticism and careful editing of the manuscript. Acknowledgements are due to the Ground Water Division, Department of Mineral Resources, Ministry of National Development, and the Department of Public and Municipal Works, Ministry of Interior of the Government of Thailand for assisting with the supply of data.

ABSTRACT

A map showing concentration iron in ground waters throughout Thailand has been developed from available data. It was found that the problem of iron in ground water existed mainly in the Northeastern part of the country.

Ferrous sulphate ($FeSO_4.7H_2O$) was added to natural ground water taken from an artesian well near Bangkok for experimental studies in the laboratory. Preliminary investigations were carried out using jar tests to determine optimum pH and optimum dose of coagulant aid required for effective iron removal before actual experiments with a laboratory - scale iron removal unit were made. Sodium hydroxide (NaOH) was used for pH adjustment and the coagulant aids used were polyelectrolytes of anionic, cationic and nonionic polymers.

A laboratory - scale unit was designed, based on the upflow solids - contact clarification process, with total detention time of 3 hours. The results obtained indicated that short-circuiting of upflow through the sludge blanket caused floc to be carried over the effluent overflow weir. Use of anionic and nonionic polyelectrolytes resulted in larger and heavier floc formation with less carry-over at the effluent overflow weir and hence improved the efficiency of the unit.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

LIST OF TABLES

LIST OF TABLES (Cont'd)

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF SYMBOLS

A = Alkalinity in mg/l as $CaCO_3$

D.O. = Dissolved Oxygen

E_h = Redox potential

K = Overall rate constant of ferrous oxidation

K_o = Logarithm of rate constant

OH^- = Molar concentration of hydroxyl ion

P_{O_2} = Partial pressure of oxygen

$T_{\frac{1}{2}}$ = Half-life in minutes, or time required for one-half of the ferrous iron in solution to be precipitated.

I - INTRODUCTION

General Introduction

Provision of adequate clean water supplies for domestic purposes has long been a critical problem for people in areas located far from permanent streams or surface water sources. The problem is particularly acute during the prolonged dry months of the summer season, during which time temporary surface water sources such as ponds become dry. With inadequate water for domestic needs, health condition may become serious, domestic animals weaken and in some instance families and livestock have been forced temporarily to other localities where water is available. Ground water in this case becomes of great importance as a valuable resource to furnish a supply of water.

Iron is one of the common contaminants associated with ground water. In rural areas ground water supplies serving villages, shcools, hospitals, and health centers often contain so much iron that they must be treated for iron removal. Yet in many cases the economy of rural areas is insufficient to support the high capital and operating costs of presently known iron removal plants incorporating sand filtration. Therefore the people often prefer to use polluted surface waters to untreated iron-bearing ground waters. There is a need to develop low cost methods of removing iron from ground waters used to serve small areas or groups of people.

Iron Problem in Thailand Ground Waters

In 1954, the Thailand Ground Water Exploration Project was implemented to evaluate the ground water potential and obtain essential information required for the orderly development of ground water supplies for domestic, municipal, stock, industrial and irrigation users in the northeastern part of the country. This area, commonly known as the "Khorat Plateau" comprises over 65,000 square miles, 33% of the total area of Thailand. The region contains 34% of Thailand population and is affected at least locally by droughts each year.

Although the wells in the northeastern area of Thailand produce safe water for domestic supplies, many of the waters contains excessive amounts of minerals. The ground water supplies are often not used even during water shortages because of the presence of high concentrations of soluble ferrous iron, which is colorless when first taken from the wells, but which turns to the reddish colored insoluble ferric state on exposure to air. Data showing iron concentration in water supplies in various regions of northeastern Thailand are shown in Appendix B. It can be seen that the iron concentrations vary from trace amounts to as high as 36.0 mg/l. In other parts of the country, concentrations of iron in ground water have been reported by the Department of Public and Municipal Works to be somewhat less than those in the Northeast, but in many cases they are found to be in excess of the upper limits recommended in the 1962 USPHS Drinking Water Standards and the International Drinking Water Standards.

According to the 1962 USPHS Drinking Water Standards, reported in AMERICAN WATER WORKS ASSOCIATION (1961), the recommended limit for iron in public water supplies is 0.3 mg/l. The International Drinking Water Standards of the WORLD HEALTH ORGANIZATION (1963) also contains the recommendation that the permissible limit of iron for potable water should be 0.3 mg/l, and a concentration of 1 mg/l is reported to be excessive. These limits are not based on any physiological consideration. Iron is, in fact, an essential mineral for proper nutrition. Limitation of the concentration of iron in water supplies is mainly due to its staining effects to the contacted materials, and supporting the growth of iron bacteria resulted in taste and odor to consumers.

Most of the ground waters in the rural areas of the country are used without treatment after pumping. Only those wells which produce acceptable quality of water are fitted with hand pumps or power pumps with elevated reservoirs. In cases wh re iron-free water sources are not available in some localities, the pumped iron bearing water from wells is held in a reservoirs for a sufficient time for the soluble ferrous iron to become naturally oxidized by the atmosphere to an insoluble iron. This is then settled out before passing on to the consumers. Works are now underway to design a simple aerator and filter system for iron removal in Northeastern

Thailand water supplies by both the Department of Mineral Resources and the Department of Health.

It was one of the purposes of this study to delineate the iron problem present in ground waters of Thailand through the preparation of a map showing iron concentration in the various areas. This map, shown in Fig.1 and accompanying data shown in Table 1, were based on available data from both the Division of Ground water, Department of Mineral Resource, Ministry of National Development and the Department of Public and Municipal Works, Ministry of Interior. In some areas in the North and in the South of Thailand there is no data available on the iron concentrations in the ground waters.

It can be seen from Fig.1 and Table 1 that although iron is present in the ground waters in many parts of Thailand, the most serious conditions are observed in the Northeast. Of the 15 Northeastern provinces only three have wells with iron concentrations as low as in the range of 2.1 mg/1 to 4.0 mg/1. The other provinces were found to be over 4.0 mg/1 up to as high as 36 mg/1 iron concentration. According to the records of chemical analyses of ground water reported by the DEPARTMENT OF MINERAL RESOURCES (1966), it was found that most of the ground waters in Northeastern Thailand are devoid of dissolved oxygen. Carbon dioxide which is often associated with iron-bearing waters, was found to range from zero in some wells to as high as 366 mg/1 in a well in Surin Province (Well No. A-11, S-10). High iron content is also

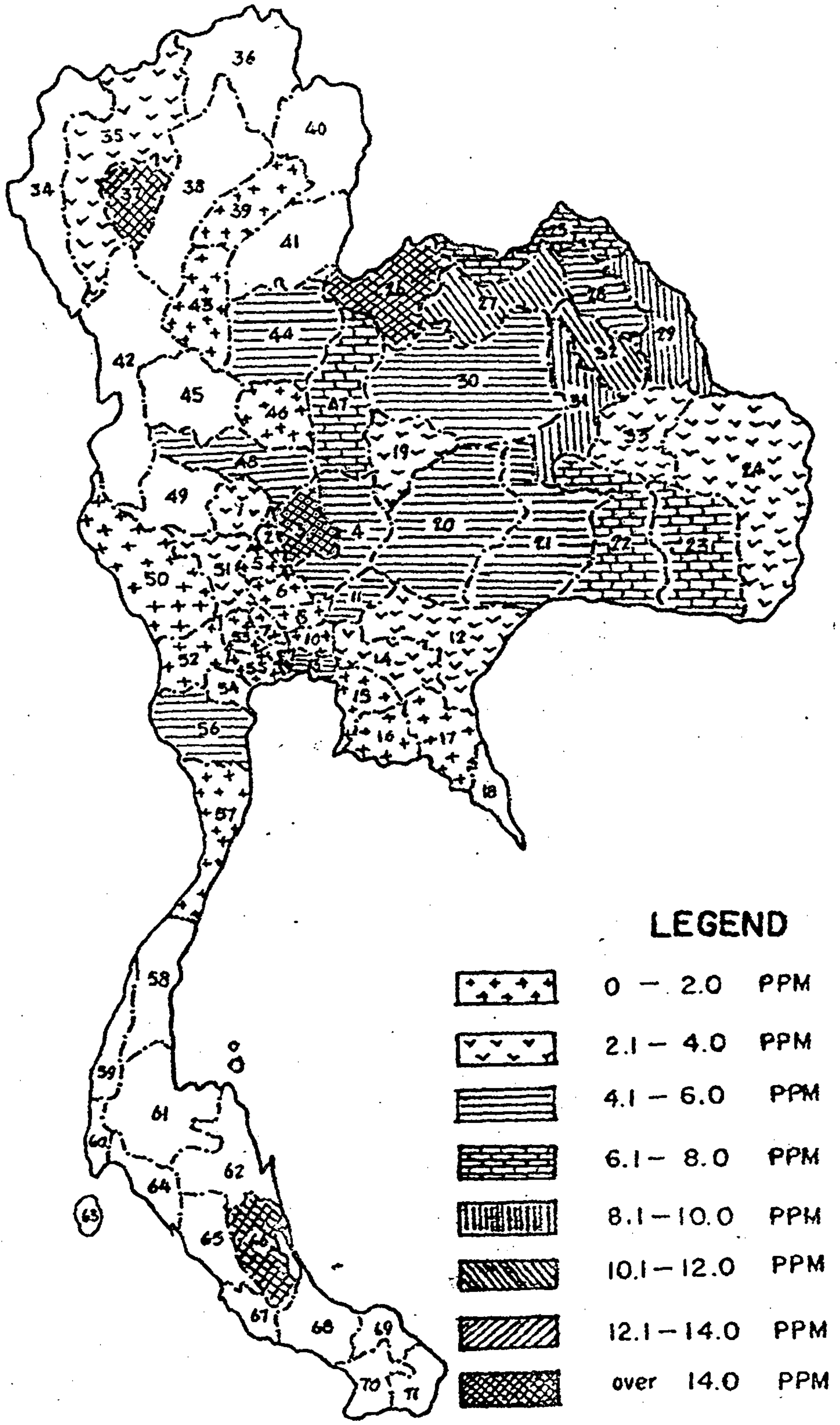


Fig.1- Map Showing Iron Concentration in Ground Water in Thailand

Legend of Fig. 1

1 Chainat
2 Sing-buri
3 Lopburi
4 Saraburi
5 Ang-thong
6 Authya
7 Nonthaburi
8 Pathum-thani
9 Thonburi
10 Bangkok
11 Nakhornayok
12 Prachinburi
13 Samutprakan
14 Cha-Choengsao
15 Cholburi
16 Rayong
17 Chanthaburi
18 Trat
19 Chayaphum
20 Nakhornratsima
21 Buri-ram
22 Surin
23 Srisaket
24 Ubonrat-Thani
25 Nong-Khai
26 Loei
27 Udron-Thani
28 Sakonnakhon
29 Nakhorn Phanon
30 Khon-Kaen
31 Maha Sarakham
32 Kalasin
33 Roi-Et
34 Mae-Hongson
35 Chiengmai
36 Chieng Rai
37 Lamphun
38 Lampang
39 Prae
40 Nan
41 Uttaradit
42 Tak
43 Sukho-Thai
44 Phitsnuloke
45 Kamphaengphet
46 Pichit
47 Phetchbun
48 Nakhorn Sawan
49 Uthai-Thani
50 Kachana-buri
51 Suphanburi
52 Ratburi
53 Nakhonpatom
54 Samutsongkhram
55 Samutsakhorn
56 Phetburi
57 Prachaup-Kairi-Khan
58 Chumphorn
59 Ranong
60 Phang-Nga
61 Surat-Thani
62 Nakhornsri-Thamrat
63 Phuket
64 Krabi
65 Trang
66 Phatalung
67 Satun
68 Song-Khla
69 Pattani
70 Yala
71 Nara-Thiwat

Province	Well depth ft.		Total Fe ppm	
	Range	Average	Range	Average
North-east				
Loei	100-191	133	1.5-36.0	14.3
Udorn	100-515	224	0.0-23.0	10.4
Nongkhai	100-480	139	0.0-21.0	6.5
Chaiyapoom	100-1004	270	2.0-10.0	3.9
Khonkhaen	90-331	198	0.0-17.0	5.4
Nkornpanom	65-845	158	0.0-28.0	9.8
Sakornnakorn	70-1045	233	0.0-23.0	5.0
Kalasin	90-526	151	1.2-41.0	11.3
Roi-ed	90-300	161	1.0-7.0	3.9
Mahasarakam	80-500	219	0.02-20.0	8.1
Surin	67-1050	329	0.6-15.0	6.7
Buriram	94-1015	275	2.5-16.0	6.0
Srisaket	100-356	179	0.5-14.0	6.4
Ubol	60-1010	246	0.0-14.0	4.0
Nakornrasima	55-1500	337	0.0-24.0	4.1
South				
Prachaupkni-rikhan	140-750	420	0.0-1.0	0.4
Songkhla	50-240	194	1.9-90.0	22.3
Chumporn	-	-	-	-
Surat-thani	-	-	-	-
Nakornsri-thamraj	-	-	-	-

Province	Well depth ft.		Total Fe mg/l	
	Range	Average	Range	Average
Pattalung	-	-	-	-
Trang	-	-	-	-
Puket	-	-	-	-
<u>North</u>				
Chiengmai	152-330	216	1.0-4.8	2.8
Lamphun	135-345	133	212-120.0	47.0
Prae	246-400	335	0.1-2.3	0.8
Uttaradit	50-250	138	2.0-25.0	8.0
Petchaboon	152-350	186	0.6-21.0	8.0
Sukhothai	60-260	146	0.6-3.3	1.9
Pitsanuloke	185-270	219	1.8-5.8	4.7
Kamphaeng Phet	-	-	-	-
Tak	-	-	-	-
Chiengrai	-	-	-	-
Lampang	-	-	-	-
Nan	--	-	-	-
Mae-Hongson	-	-	-	-
<u>Central</u>				
Nakonsawan	131-287	218	0.2-6.5	5.0
Pichit	150-310	225	0.8-2.3	1.5
Chainat	35-231	120	0.4-7.0	2.7
Lopburi	66-320	189	0.0-80.0	30.0
Saraburi	100-258	159	0.0-42.0	5.9

Province	Well depth ft.		Total Fe mg/1	
	Range	Average	Range	Average
Singhburi	170-354	225	0.2-1.0	0.3
Supanburi	144-187	165	1.4-5.0	3.8
Ayudhaya	167-365	245	0.1-1.0	0.4
Pratumthani	248-364	293	0.2-0.8	0.5
Nontaburi	565-720	596	1.0-2.1	1.5
Bangkok	400-713	590	0.1-1.3	0.8
Thonburi	481-670	559	0.1-4.8	1.0
Samutprakan	403-903	689	0.5-11.0	5.2
Samutsakorn	355-542	472	0.1-1.6	1.0
Angthong	112-174	143	0.1-0.2	0.2
Rachaburi	130-660	305	0.2-1.8	1.0
Petchaburi	200-850	562	0.3-17.0	5.0
Nakornpatom	302-645	401	0.1-0.7	0.3
Kanchanaburi	113-215	165	0.2-2.8	1.5
Utai-thani	-	-	-	-
Samutsongkam	-	-	-	-
<u>East</u>				
Cha-Choengsao	295-580	438	1.8-3.8	2.8
Rayong	45-84	66	0.8-3.3	2.0
Cholburi	141-160	145	0.3-2.4	1.3
Prachinburi	80-215	135	0.0-7.0	2.2
Chantaburi	74-75	74	0.8-1.2	1.0
Nakonnayok	80-320	152	1.0-9.0	5.5
Trat	-	-	-	-

Note: See APPENDIX B for additional data on individual wells.

commonly associated with a high concentration of hardness, and some wells in Northeastern Thailand exhibited total hardness, more than 1,000 mg/l expressed as $CaCO_3$. Manganese was reported to be relatively low compated with iron and other constituents. The major constituents which were found in high concentrations in the ground waters in this area were Ca^{++}, Mg^{++}, K^{+}, Fe^{++}, HCO_3^{-}, $SO_4^{=}$, Cl^{-} and $PO_4^{\equiv}$

HAWORTH, NA CHIENGMAI and PHIAN CHAREON (1966) reported in their ground water resources development study of Northern Thailand that the concentration of iron in water of sand stone aquifers was slightly lower than in shale and siltstone aquifers. The concentration of iron in water from limestone was moderately high, because the most important source is iron pyrites ($Fe\ S_2$) which is easily attacked and dissolved by water containing carbon dioxide.

In the central part of the country, higher iron concentration in ground water appears to be not as common as in the Northeast. Most of the deeper wells produce a more acceptable quality of ground water than the shallow ones.

Purposes of the Study

The primary objective of this study was to obtain information which could be used to improve the present costly process of iron removal. It included also a study of the fundamental factors that govern oxidation of soluble ferrous iron to the insoluble ferric form so that ferric precipitates could be removed by sedimentation. The main purpose of the study was to develop, on a laboratory - scale, a unit combining the oxidation, flocculation and upflow solids contact clarification processes into one with sufficient efficiency in order to avoid the necessity of using rapid sand filters, commonly employed in conventional iron removal processes. Such a unit can be operated by untrained personnel in rural areas where funds are limited.

Scope of the Study

Ground water from an artesian well located near Bangkok with characteristics similar to most of the ground waters in the northeastern part of Thailand was selected as the raw water for the study. Because of relatively low iron content in the ground water from this well, ferrous sulfate - ($FeSO_4.7H_2O$) was added to produce ground water of high iron concentration similar to that commonly found in the northeastern part of the country.

The study was carried out in the laboratory in two major steps:

Preliminary Investigations Preliminary investigations were first made to determine an optimum pH for iron removal. Jar tests were carried out with water having pH values of 7.0,7.5,8.0,8.5,9.0 and 9.5. Adjustment of pH was made by the addition of NaOH. The optimum pH value so obtained was then employed in the laboratory-scale iron removal unit, and it was found that the iron flocs were light and gelatinous in form, resulting in a large number of flocs being carried over to the effluent overflow weir.

In order to improve the iron floc formation in the upflow solids contact clarification employed in the laboratory-scale iron removal unit, coagulant aids were used. The coagulant aids used were organic, high molecular weight polyelectrolytes (also called "flocculant" by MINZ, 1964) of cationic, anionic and nonionic characters taken from various manufacturers, namely, nonionic PURIFLOC N-11 and N-17 and anionic PURIFLOC A-22 from the Dow Chemical, U.S.A., cationic Nalco-600 and Nalcolyte-605 from the Nalco Chemical Company U.S.A. and tannin-based FLOCCOTAN from the Forestal Industries (U.K.) Ltd. The dosing range of each coagulant aid was strictly in accordance with the manufacturer's recommendations. The optimum dose of the coagulant aids was first determined at pH 8.3 The optimum pH for the optimum dose of each coagulant aid was again determined at the original pH of the raw water for the jar test experiments.

Another study on coagulant aid was made with Bangkok clay. The clay was added to the ground water to prepare a series of solutions with turbidity values of 25,50,75,100 and 125 units. A Jackson candle turbidimeter was used for measurement of turbidity. The prepared series of ground waters was then supplemented with 50 mg/l $FeSO_4.7H_2O$. Determination of the turbidity and the residual iron in the decanted supernatant after 2-hour settling period was then carried out. This test was repeated using 25 mg/l $FeSO_4.7H_2O$.

Experimental Investigations Experiments with the laboratory-scale iron removal unit were carried out at the optimum pH and with the optimum dose determined during preliminary investigations described above. The first run was operated with the pH value in the flocculation chamber controlled within the range of 8.0 to 8.7, without coagulant aid. In the second run, the water was dosed with 5.0 mg/l anionic FLOCCOTAN; the third run with 2.0 mg/l cationic Nalco-600 and the fourth run with 2.0 mg/l nonionic PURIFLOC N-11. During the experiments with the laboratory-scale iron removal unit, the total flow rate of the raw water, NaOH and coagulant aid solution of each run was controlled at about 54 ml/min in order to get 3-hour detention time in the unit.

II - LITERATURE REVIEW

LONGLEY, ENGELBRECHT and MARGRAVE (1962) designed a pilot plant for both laboratory and field experiments to study the fundamental factors that govern the removal of iron by oxygenation, sedimentation with flocculation, and plain sedimentation. Their pilot plant also included a rapid sand filter. Oxygenation was accomplished by using a multiple-pass aerator with diffused air. It was found that the dissolved oxygen of the effluent could be brought up to 6.36 ± 0.8 mg/l. The reaction basin had the combined purpose of providing time for completing the chemical reaction and for flocculation and sedimentation. It had a 1.5-hour detention time at a flow rate of 0.12 gpm. The rapid sand filter consisted of a 30-inch depth of sand with a design loading of 2 gpm/sq.ft. The filter medium was screened, sharp grained sand, having an effective grain size of 0.45 mm and a uniformity coefficient of 1.4. The results of this investigation using an essentially standard water treatment process can be summarized as follows:

1. The ranges of iron removed by each unit process of the pilot plant, based on the amount of iron applied to that unit were:

Process	Removal - %
Aeration	0.1 - 44
Reaction Basin	0 - 13
Filtration	96 - 100

2. It was found that the following had no effect on

overall iron removal efficiency:

Substances	Amount , mg/l
Chlorides	0 - 60
Sulfates	0 - 75
Total nitrogen	0 - 16
Total hardness	427
and Chemical Oxygen Demand	0 - 65.2

3. Alkalinity values greater than 400 mg/l and in excess of the hardness present favored more rapid oxidation of iron.

LONGLEY and others (1962) also made an investigation into the role of filtration in iron removal. It was found that there was often a depletion in dissolved oxygen in the water as it was filtered. This resulted in a high iron content, usually in the ferrous form, in the finished water. It appeared that the bacterial growth which developed in the filter and the amount of iron passing through the filter increased with time of filtration following each backwash cycle. The depletion of dissolved oxygen as a result of bacterial growth led to the development of a reducing enviornment and was accompanied by a slow decrease in the oxidation - reduction potential within the filter as filtration proceeded.

GHOSH, OCONNOR, and ENGELBRECHT (1966) studied factors that govern the kinetics of iron precipitation in natural ground waters in order to find a more rational approach to the engineering design of reaction basins in iron removal plants. Investigations were conducted at eight water treatment plants in central Illinois. An 8-liters sample of ground water was aerated for 2 minutes to raise the dissolved concentration to 6 mg/l or more. Laboratory studies indicated that the rate of iron precipitation was unaffected by dissolved oxygen if its concentration exceeded 5 mg/l. A plot of the log of the ferrous iron concentration in solution versus reactive time was found to be linear, indicating that the precipitation of ferrous iron from solution was governed by a first order reaction with respect to ferrous iron concentration. The relationships between the ferrous iron remaining in solution and the time following aeration are shown in Fig.2. As the water samples were drawn from different sources with varying pH values, it was difficult to draw any definite conclusion from the curves alone.

On the other hand, if the experimental results were rearranged and a plot of equilibrium pH versus the rate of precipitation, as half life, $T\frac{1}{2}$, for the Illinois ground water studied as shown in Fig. 3 was made, a somewhat remote relationship between pH and rate of precipitation was indicated, showing precipitation occurring more rapidly at higher pH levels. Conversely, a comparison of alkalinity and precipitation rate indicated that higher alkalinities were associated with shorter half life or more rapid precipitation rates.

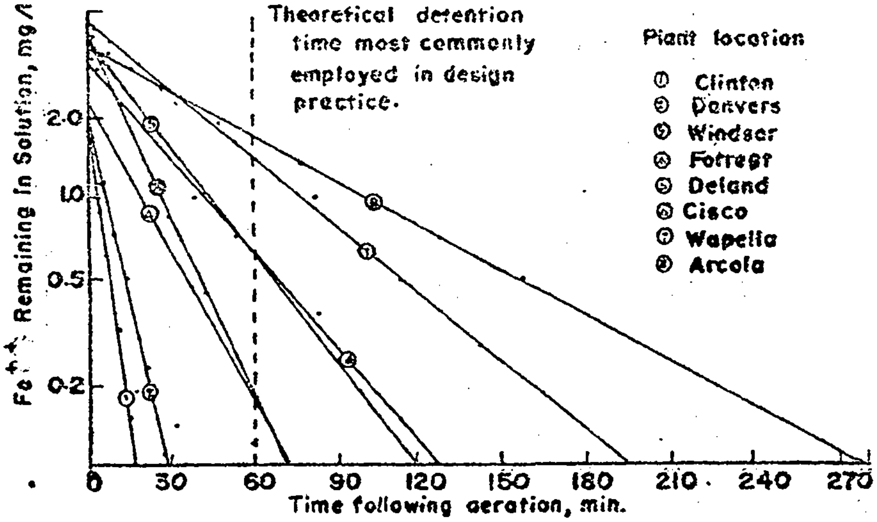
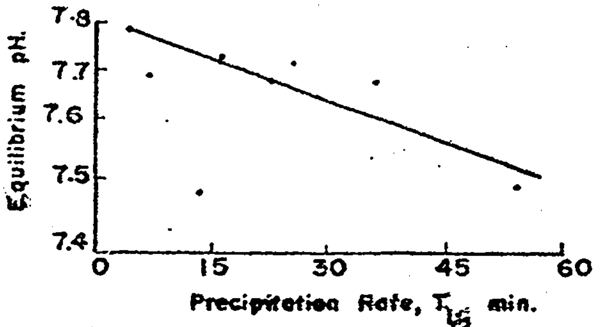


Fig. 2- Precipitation of Iron in Illinois Ground water afte GHOSH and others (1966)



Equilibrium pH Versus Precipitation Rate

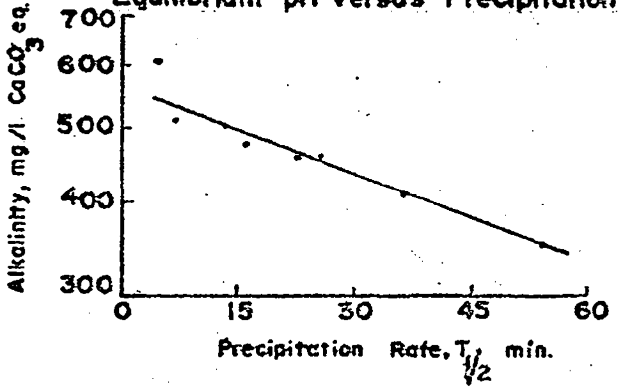


Fig. 3 — Alkalinity versus Precipitation Rate after GHOSH and others (1966)

The dependency of iron precipitation on alkalinity was shown to have the form :

$$T_{1/2}\ (\text{min}) = 522 -- 0.33\text{x}10^{14}(\text{OH}^-) - 183.\log\ (\text{alkalinity}) \pm 8.10 \qquad (1)$$

This empirical expression was derived from data on water having equilibrium pH values ranging from 7.5 to 7.8 and alkalinities in the range of 355 - 610 mg/l as $CaCO_3$. A conclusion that may be drawn from the large alkalinity dependency of the precipitation rate is that the precipitates formed were primarily carbonates rather than hydroxides, and a large part of the iron precipitated from Illinois ground waters was in the ferrous, rather than ferric form.

STUMM and LEE (1961) studied the reaction between ferrous iron and oxygen and found that the rate of oxygenation was a function of ferrous iron concentration and the partial pressure of oxygen (P_{O_2}), as indicated by Eq. 2.

$$-\frac{d(\text{Fe}^{++})}{dt} = K^1\ (\text{Fe}^{++})\ P_{O_2} \qquad (2)$$

In their study of the effect of pH on the rate of oxidation of ferrous iron, their data indicated a 100 - fold increase in the rate with an increase of one pH unit. Because of this second order relationship with respect to hydroxyl ion concentration, the overall rate was expressed as :

$$-\frac{d(\text{Fe}^{++})}{dt} = K(\text{Fe}^{++})\ P_{O_2}\ (\text{OH}^-)^2 \qquad (3)$$

where

$$K = \frac{K^1}{(\text{OH}^-)^2}$$

$$K^1 = \frac{Ko}{P_{O_2}}$$

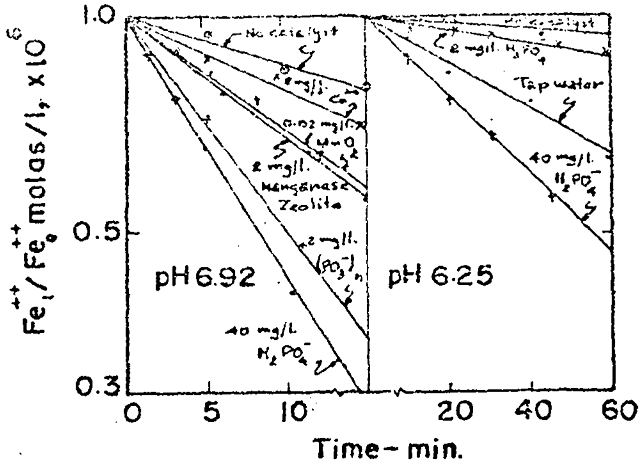


Fig. 4- Effect of Some Chemical Catalysts on the Iron Oxidation after STUMM and LEE (1961)

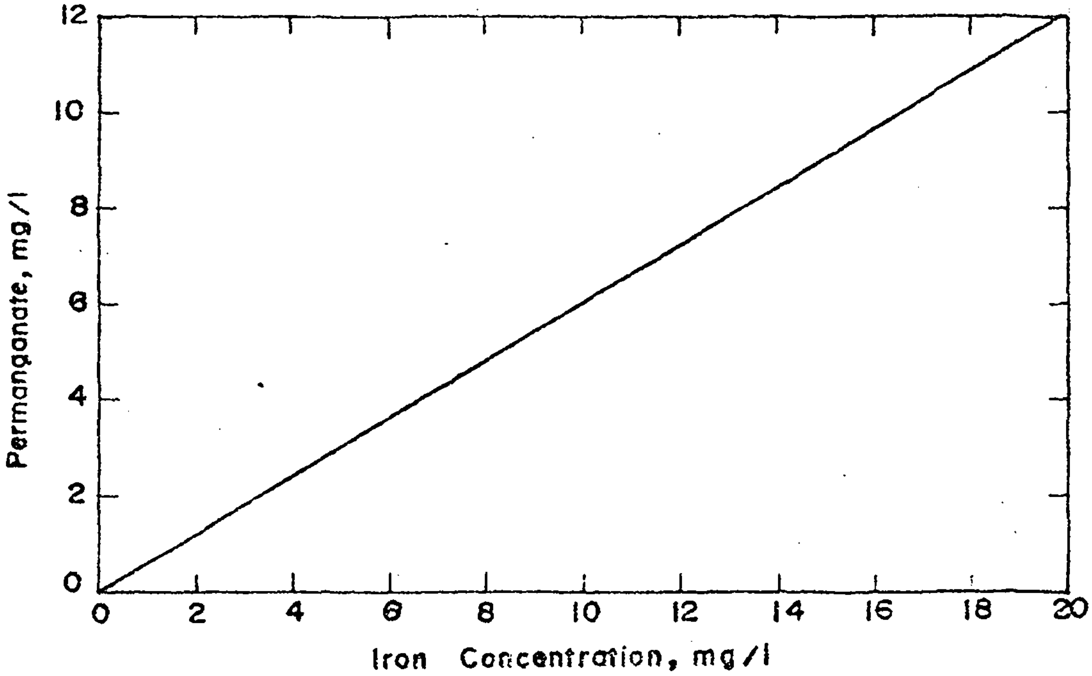


Fig. 5- Permanganate Demand Curve for Oxidation of Ferrous Iron after WILLEY and JENNINGS (1963)

$$Ko = \frac{-d\ln(Fe^{++})}{dt}$$

and Ko = logarithm of the rate constant

Another study was made by the same authors (1961) on catalytic effects in iron oxidation. They found that metal ions of Cu^{++}, Mn^{++} and Co^{++} as well as anions like $H_2PO_4^-$, in addition to OH^-, formed complexes such as $Fe^{+++}(H_2PO_4)_3^-$ and were capable of hastening the oxygenation reaction. Fig.4 shows the effect which trace quantities of some chemical catalysts exhibited in accelerating the oxidation reaction.

BABCOCK (1950) studied the efficiency of the Spaulding Precipitator, in which, a sludge blanket was suspended in the tank by the velocity of the influent and acted as filter and catalytic surface for the removal of iron and manganese from the water. He reported that the use of the precipitator caused removal of approximately 95% of iron and manganese, if a pH value within the range 8.5 to 9.1 was maintained during operation. The chemicals used were alum and lime. No coagulant aid was employed.

BENSON (1965) developed a simple method to remove gross quantities of iron in remote Alaskan water supplies. He used a fill - and - draw treatment tank with slaked lime, $Ca(OH)_2$, as the chemical to adjust the pH and precipitate the iron, followed by decantation and disinfection of the treated water by chlorination. In the case of ground water with high carbon dioxide, aeration, using a small gasoline - powered compressor to diffuse air into the treatment tank, was carried out prior to chemical treatment.

Concentrations of iron, manganese, hardness and alkalinity were greatly decreased, but the pH of the effluent was as high as 10.8.

WILLEY and JENNINGS (1963) discussed the use of potassium permanganate ($KMnO_4$) to oxidize ferrous iron to insoluble ferric precipitate. They suggested that dissolved iron and manganese can be effectively removed from water by continuous feeding of potassium permanganate to water before it is passed through a manganese green sand filter. This method has been known as a continuously-regenerating process. The quantity of potassium permanganate required can be determined by running a permanganate demand test on the water to be treated. The reactions involved are:

$$3Fe(HCO_3)_2 + KMnO_4 + 7H_2O \rightarrow MnO_2 + 3Fe(OH)_{3\downarrow} + KHCO_3 + 5H_2CO_3 \quad (4)$$

Theoretically, one part of potassium permanganate ($KMnO_4$) will oxidize 1.06 parts of soluble ferrous iron to insoluble ferric iron. In practice, it was found that a less amount of potassium permanganate was required due to the secondary reaction of the MnO_2 formed, according to the following equation:

$$2\,Fe^{++} + 2MnO_2 + 5H_2O \rightarrow 2Fe(OH)_{3\downarrow} + Mn_2O_3 + 4H^+ \quad (5)$$

They also developed a permanganate demand curve for oxidation of ferrous iron as shown in Fig.5. This curve shows the permanganate concentration required to oxidize ferrous iron completely in the given concentrations.

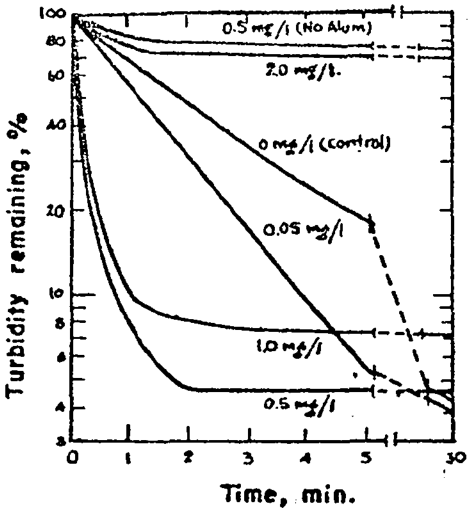


Fig. 6-Effect of Anionic Flocculant after COHEN and Others (1958)

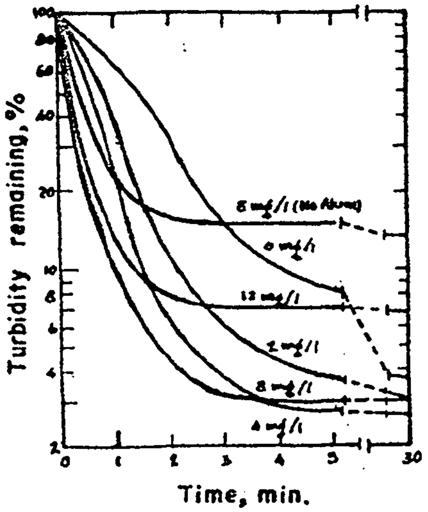


Fig. 7- Effect of Cationic Flocculant after COHEN and Others (1958)

COHEN and others (1958) studied the effect of three types of flocculant: anionic A, cationic B and nonionic C, on both artificially prepared clay suspensions and different natural waters. Containers with stirrers were used for the tests. An optimum dose of aluminum sulfate was added to the process water, with different doses of the test flocculant, and mixing was continued for 30 minutes, followed by 30 minutes settling. The effect of anionic flocculant A on floc settlement during the treatment of water artificially made turbid with clay is shown in Fig. 6.

The best results were obtained with a flocculant dose of 0.5 mg/l. Further increase of dosage caused a reduction in the settling rate and higher residual turbidity. At 2 mg/l, settling was practically inhibited. This result indicates that the flocculant is effective within a given dosimetric range and that there is an "optimum" dose at which optimum settling is obtained. When an anionic flocculant was added to the water without aluminum sulfate no coagulation or settling was produced. Similar results were obtained in treating natural waters.

The effect of cationic flocculant B is shown in Fig.7, plotted from test results in the treatment of Ohio river water. The cationic flocculant, like the anionic, considerably raised the settling rate at optimum doses. But, in contrast to the anionic flocculant, it produced a definite effect without aluminum sulfate, and allowed the proportion of this latter reagent to be considerably reduced.

Comparing the effects of different types of flocculants, the authors showed that the least effective and versatile flocculant was the nonionic flocculant C, which reacted only in the case of one process water out of all those with differing composition and physio-chemical properties that were tested. Flocculant B was ineffective with weakly mineralized waters.

MINZ (1964) discussed the use of polyelectrolytes as coagulant aids in water purification processes. In order to approach the mechanisms of the polyelectrolyte in facilitating flocculation, the author presented a model of a structure of floc formed by cogaulation in treatment of turbid water as shown in Fig.8. He discussed that when coagulants were used in turbid water coagulation, the coagulant furnished ionic charges opposite to those of suspended and colloidal particles resulting in neutralization of repelling charges on the particles. The particles in suspension became covered with adsorbed colloidal particles of the hydroxide of the coagulant which had joined each other to form "adhesive bridge" thus linking together the suspended particles. The space lattice contained "trapped" water which is incorporated into the structure of the flocculated particles. The mechanical entrapment of the agglomerated particles by adsorption on to the floc formed with coagulant chemicals and also by molecular bridging of the individual molecules of the coagulant is known as "Flocculation".

When the polyelectrolyte was used as coagulant it acted as a "binder" or "bridger" in that it mechanically entrapped or stuck

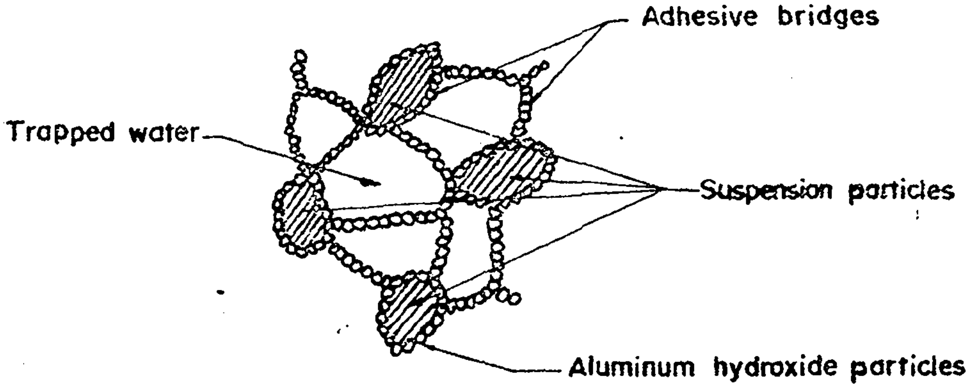


Fig. 8– A Model of a Structure Floc formed by Coagulation in the Treatment of Turbid Water after MINZ et al (1955)

floc particles together by their opposite electrical and surface charges thus caused an increase in floc strength and an acceleration of floc formation. The flocculation rate depended on the number of segments of the polymolecule arranged along its chain, suitable for being adsorbed onto the particle surfaces. The polyelectrolytes were effective within a given dosage range. If the polymer was added in excess, its molecules were also completely adsorbed on suspended particles and stabilized the suspension, as a protective colloid thus inhibiting flocculation.

Iron Removal Processes

A number of processes can be used, singly or in combination for the treatment of iron bearing waters. The choice of the process depends upon the range of the quality of the raw water and upon the chemical state of the iron compounds. Iron removal methods may be clarified as oxidation, chemical or ion exchange.

Oxidation Methods

Aeration - On aeration, iron present in the soluble ferrous form is converted to insoluble hydrated ferric oxide which can be removed by settling and filtration. The chemical reaction may be shown as :

$$4\ Fe^{++} + (2x+4)H_2O + O_2 \rightarrow 2Fe_2O_3.xH_2O\downarrow + 8H^+ \qquad (6)$$

Stoichiometrically, 1 mg/l of oxygen will be required for 7 mg/l of ferrous iron.

Aeration is usually employed in ground waters where iron is present as ferrous bicarbonate. The aeration of such ground waters results in the formation of CO_2 as shown in Eq. 7.

$$4\ Fe\ (HCO_3)_2 + O_2 + 2H_2O \rightarrow 4\ Fe(OH)_{3\downarrow} + 8\ CO_2 \qquad (7)$$

The CO_2 thus formed in addition to that which may already be present in the ground water, is stripped from the water to a considerable degree only by a sufficient pressure of oxygen from an aeration process. Any CO_2 present will react with the water as shown in Eq. 8.

$$H_2O + CO_2 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^= \qquad (8)$$

The H^+ ions then neutralize the OH^- groups on hydrous ferric oxide floc. If sufficient H^+ ions are present, they cause high affinity for the floc and produce positively-charged particles. A high positive charge causes an increase in the electrokinetic repelling force among the particles and they will not coagulate as readily again.

Any factor which tends to displace this equilibrium may determine the course of iron removal. This can be brought about through removal of carbon dioxide causing an increase in pH or depression of the hydrogen ion concentration and thus favoring removal of iron. Removal of carbon dioxide although easily accomplished by aeration, may also be carried out by neutralization through the addition of alkaline substance such as slaked lime, $Ca(OH)_2$, soda ash (Na_2CO_3) or caustic soda (NaOH).

Aerators can be classified into four main groups, namely those in which water flows or falls through air, such as coke trays, slat-trays and spray aerators; diffused aerators in which air is bubbled through the water in an open tank; rotating brushes, in which air is induced into the water by surface agitation; and injector aerators, in which air is allowed to dissolve under pressure in a closed tank.

Aeration followed by sedimentation has been utilized somewhat ineffectively in the past as a simple iron removal water treatment scheme. Settling is necessary after aeration to remove the insoluble hydrated ferric oxides formed, but it has not usually added greatly to the effectiveness of iron removal unless large quantities of iron were present. In addition to the precipitate, a rather stable sol is often formed upon simple aeration. It does not settle well and gives a rather opalescent appearance to the water. Thus filtration has been necessary to polish the settled effluent.

Filtration has been commonly employed in iron removal plants. Short filter runs have resulted from the clogging of the pores between sand grains in the filters by iron floc particles remaining after the sedimentation process. A reduction of iron from the ferric to the ferrous state also occurs during filtration, and is associated with a marked depletion of dissolved oxygen and a considerable growth of biological slime in the filters.

Chlorine or hypochlorite - Chlorine or hypochlorite are effective oxidizing chemicals for oxidizing iron to insoluble forms even at low pH values. The reaction may be represented as:

$$2\ Fe(HCO_3)_2 + Ca(HCO_3)_2 + Cl_2 \rightarrow 2Fe(OH)_3\downarrow + CaCl_2 + 6CO_2 \qquad (9)$$

From this equation, it can be calculated that 1.6 mg/l of chlorine are required to oxidize 7 mg/l of iron. A.W.W.A. (1951) reported that chlorine acted in two independent ways : first, it destroys the complex compounds of iron and manganese, and thus modifies them so that they may be readily oxidized; second either the chlorine or the dissolved oxygen chlorine dose may be reduced through partial oxidation by preliminary aeration.

Potassium permanganate ($KMnO_4$) - Potassium permanganate can be used either for direct oxidation of ferrous into soluble ferric iron, or, indirectly, for regeneration of manganese zeolites or green sand beds. The reactions involved in oxidation of iron have been shown in Eq. 4 and 5.

Manganese zeolite or green sand is manufactured by treating New Jersey glanconite with manganous sulfate and potassium permanganate to provide an active supply of higher oxides of manganese on the grains of sand. This manganese zeolite or green sand has been used fairly effectively as a filter medium to oxidize and remove iron and manganese from water. Potassium permanganate is used to regenerate the sand grain surfaces when the oxidizing power of the bed has been exhausted.

The use of potassium permanganate to regenerate the exhausted green sand bed can be in the form of intermittent doses each time the oxidizing power of the bed has been exhausted, which is known as a regenerative batch process, or by continously regenerating the green sand by permanganate feed to the incoming water. The regenerative batch process has the disadvantage that the bed is exhausted quickly if other reducing substances such as organic matter, nitrogenous matter or hydrogen sulfide (H_2S) are present. A substantial excess of permanganate is then required in regeneration. The continuously-regenerating process has the advantage of utilizing the full oxidation potential of potassium permanganate as well as manganese dioxide. If the amount of iron in the raw water is high in relation to permanganate dose, then the excess is removed by the green sand. Conversely, if the permanganate dose is in excess of that required, then this excess is utilized in regenerating the green sand.

Ozone - can be used to oxidize iron and manganese to insoluble forms and is particularly useful when color or taste and odor problems occur at the same time.

Chemical Methods

Lime treatment - Iron can be precipitated from aerated ground water by the addition of lime. OWEN (1963) described a process using calcium hydroxide, $Ca(OH)_2$, for precipitation of iron and manganese. He found that a pH of 8.4 was required for complete removal of iron. BABBITT, DOLAND and **CLEASBY** (1959) stated that a pH of 8.2 is needed for the precipitation of iron. The chemical reactions involved are shown in Eq. 10 and 11.

$$Fe(HCO_3)_2 + Ca(OH)_2 \rightarrow Fe(OH)_2 + Ca(HCO_3)_2 \qquad (10)$$

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3\downarrow \qquad (11)$$

Lime also has an advantage in treatment of soft well-waters devoid of oxygen and containing ferrous bicarbonate. Aeration in this case cannot be employed, since it will bring about corrosion when the water is treated with lime in a closed system, the insoluble ferric iron formed will be removed in a closed settling tank or in pressure filters.

Coagulation - Highly turbid colored surface waters containing colloidal iron or iron bound with organic matter can be treated for iron removal by the application of a coagulant such as aluminum sulfate or alum, $Al_2(SO_4)_3.14H_2O$, or ferric chloride, Removal of the turbidity or colloidal particles with also remove the iron associated with them. Adjustment of pH is often necessary to secure optimum results.

Ion-exchange Method

Conventional cation-exchange softening units will remove iron and manganese when present in the soluble ferrous state, just as calcium and magnesium are removed. Any prior aeration of the water will result in the accumulation of precipitated oxidized iron on the resin surfaces, thus interfering with effective base exchange. If this occurs, inhibited hydrochloric acid or other resin cleaner is needed in the regenerative process.

III THEORETICAL CONSIDERATIONS

Mechanism of Solution of Iron

Iron occurs in almost all soils and rocks in the forms of oxides, sulfides and carbonates. As an oxide it may appear as ferrous oxide or red hematite (Fe_2O_3), magnetite (Fe_3O_4), or brown hematite or limonite ($2Fe_2O_3.3H_2O$). As carbonate it occurs as siderite ($FeCO_3$), and iron in the sulfide form is known as iron pyrites (FeS).

In ground water, iron commonly exists in the soluble ferrous state. The mechanisms by which iron may enter ground water, according to GHOSH (1965) are as follows :

a) solution due to the presence of excess CO_2, which possibly results from bacterial reactions converting insoluble ferrous carbonate, ($FeCO_3$), into highly soluble ferrous bicarbonate, $Fe(HCO_3)_2$, as typified by Eq. 12 :

$$FeCO_3 + H_2O + CO_2 \rightleftarrows Fe(HCO_3)_2 \qquad (12)$$

b) solution under anaerobic conditions, possibly due to the presence of soil bacteria, which reduce ferric iron to the ferrous form in the first step, often which it is dissolved by CO_2 as shown in Eq. 13 and 14:

$$2Fe_2O_3 + \text{organic matter} \rightarrow 4FeO + CO_2 \qquad (13)$$

$$FeO + 2H_2O + 2CO_2 \rightarrow Fe(HCO_3)_2 + H_2O \qquad (14)$$

c) solution of organic color bodies from vegetative growths in which iron, both ferrous and ferric, is complexed with stable organic compounds. This type of water is commonly found when the source is a swampy area.

Factors Influencing Iron Removal

Important factors to be taken into account in iron removal processes have been discussed extensively by many investigators. GHOSH and others (1966) have conlcuded from their studies that the factors are primarily as follows:

Solubility of iron Table 2 shows solubility equilibria of iron after GHOSH (1965). Graphs developed from these equilibrium values showing solubility of $Fe(OH)_{2(s)}$ (ferrous hydroxide in solid phase) in non-carbonate and non-sulfide solution are shown in Fig.9. The solubility of ferrous iron in carbonate bearing waters and the solubility of $Fe(OH)_{3(s)}$ (ferric hydroxide in solid phase) are shown in Fig.10 and Fig.11 respectively.

A comparison of Fig.9 with Fig.10 indicates that any form of alkalinity reduces the solubility of the bivalent iron considerably. For example, at pH 9.0, the total soluble ferrous iron in a non-carbonate water as seen from Fig.9, is $5x10^{-5}$ mol/l (2.8 mg/l) whereas in a carbonate bearing water (total alkalinity 10^{-2} eq./l or 500 mg/l as $CaCO_3$), it is seen in Fig.10 that the solubility is $3.16x10^{-7}$ mol./l. This shows that ferrous iron existing in a carbonate-bearing water will have more tendency to form crystal nuclei and precipitate than if the iron is in a non-carbonate water at the same pH of 9.

Fig.11, shows the solubility characteristics of trivalent iron. This solubility is limited by the equilibria of ferric hydroxide, $Fe(OH)_{3(s)}$. As pH 9.0 the concentration of total trivalent iron that can exist in saturation equilibrium with

Table 2 - Equilibria for Iron, after GHOSH (1965)

No.	Equation	Equilibrium constant at 25°C
1	$Fe(OH)_{2(s)}^{*} = Fe^{+2} + 2OH^{-}$	8×10^{-16}
2	$Fe(OH)_{2(s)} = FeOH^{+} + OH^{-}$	4×10^{-10}
3	$FeCO_{3(s)} = Fe^{+2} + CO_3^{=}$	2.11×10^{-11}
4	$FeCO_{3(s)} + OH^{-} = FeOH^{+} + CO_3^{=}$	5.05×10^{-16}
5	$HCO_3^{-} = H^{+} + CO_3^{=}$	4.7×10^{-11}
6	$Fe(OH)_{2(s)} + OH^{-} = Fe(OH)_3^{-}$	8.3×10^{-6}
7	$Fe(OH)_{3(s)} = Fe^{+3} + 3OH^{-}$	6.6×10^{-38}
8	$Fe(OH)_{3(s)} = Fe(OH)_2^{+} + (OH)^{-}$	5.13×10^{-17}
9	$Fe(OH)_{3(s)} = FeOH^{++} + 2OH^{-}$	2.57×10^{-26}
10	$Fe(OH)_{3(s)} + OH^{-} = Fe(OH)_4^{-}$	10^{-5}
11	$H_2O = H^{+} + OH^{-}$	10^{-14}
12	$Fe(OH)_{3(s)} = Fe(OH)_{3(d)}^{**}$	2.9×10^{-7}

* $Fe(OH)_{2(s)}$ means ferrous hydroxide in solid phase.

** $Fe(OH)_{3(d)}$ means undissociated $Fe(OH)_3$ in solution.

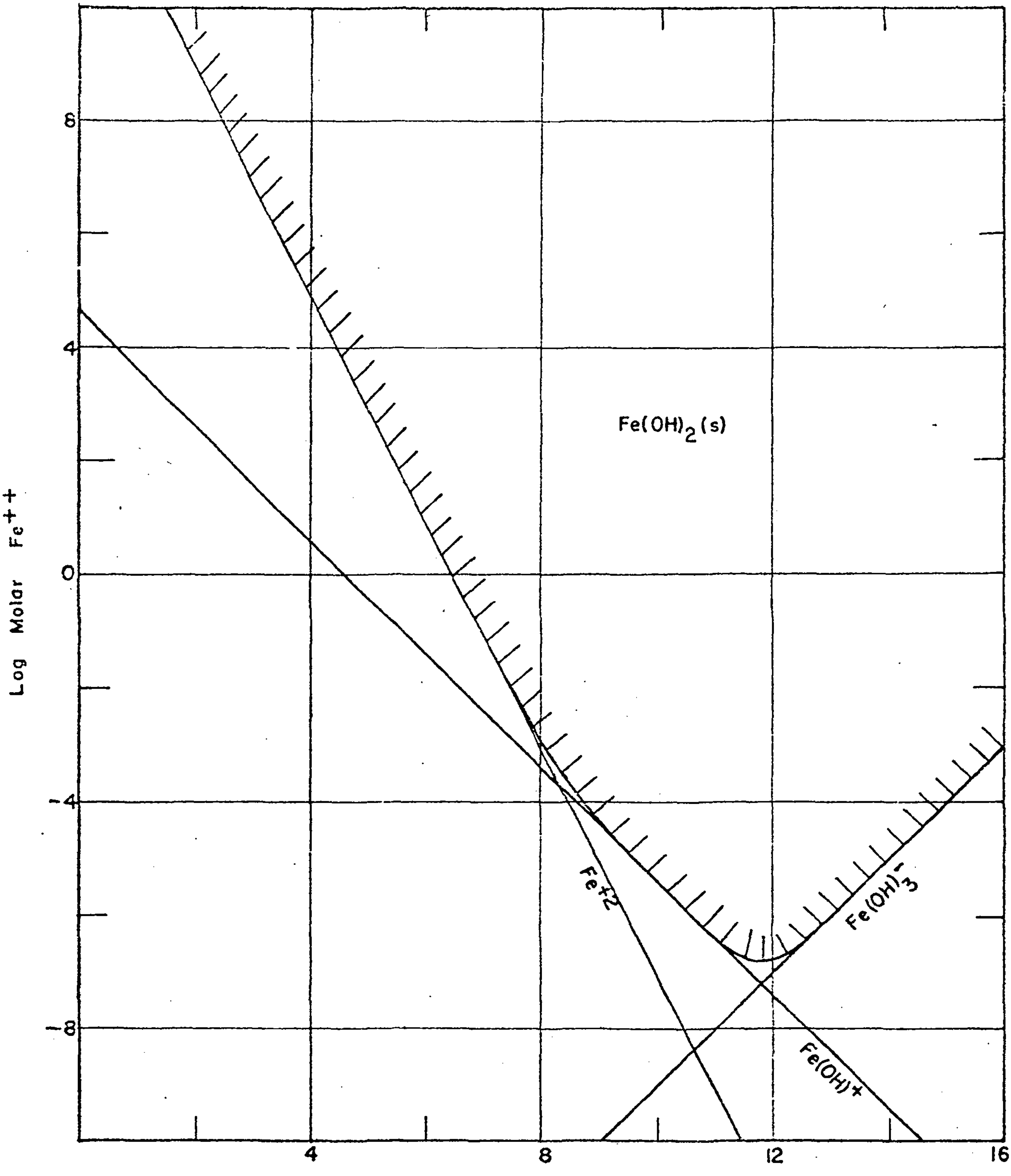


Fig. 9-Solubility of Fe(OH)$_{2(s)}$ in a Non-Carbonate, Non-Sulfide Solution

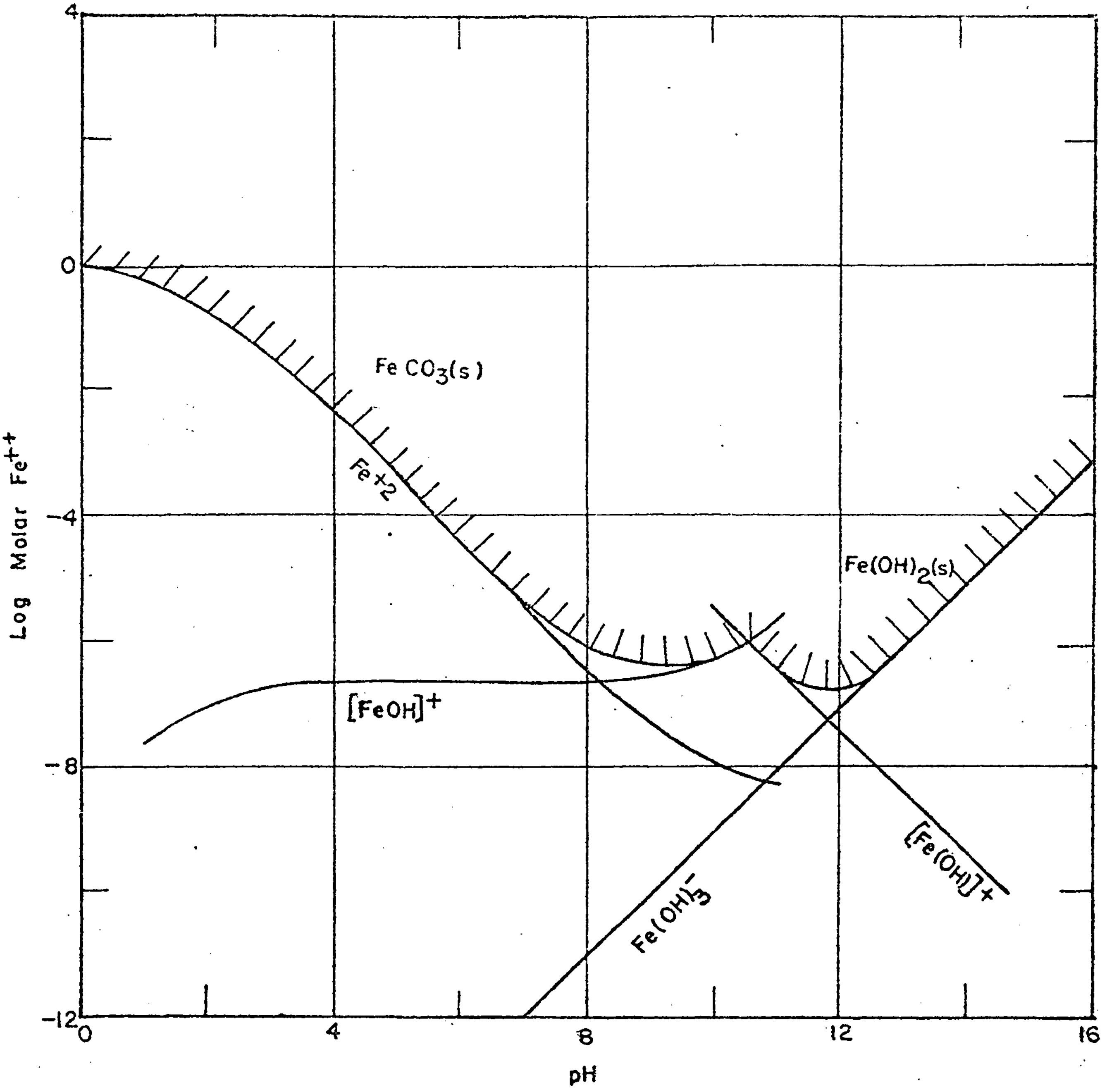


Fig. 10 - Solubility of Ferrous Iron in a Carbonate-Bearing Water (Alk.= 10^{-2} eq./l)

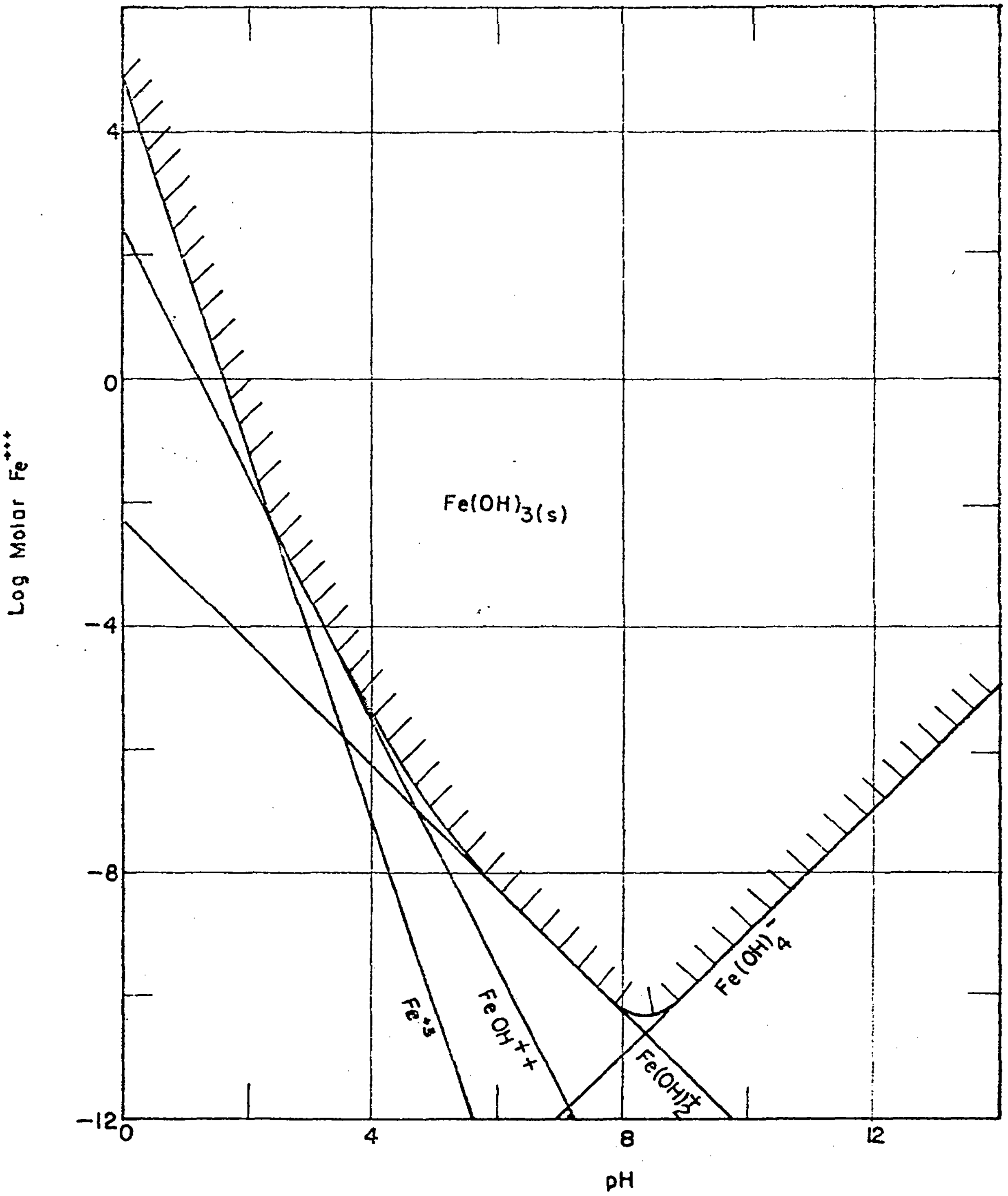


Fig. 11 —Solubility of $Fe(OH)_{3\,(s)}$

$Fe(OH)_{3(s)}$ is 10^{-10} mol./1 ($5.6x10^{-6}$ mg/1). This also indicates that at pH 9.0, ferric hydroxide has more tendency to precipitate than the ferrous form in carbonate-bearing water. The solubility of ferric iron may be much higher if it is complexed with organic or inorganic ligands other than the hydroxyl group (OH^-).

Oxidation kinetics of ferrous iron The basic equation describing the oxidation of ferrous iron by oxygen is given as:

$$4Fe^{++} + {}_2 + 10H_2O \rightarrow 4Fe(OH)_3\downarrow + 8H^+ \qquad (15)$$

Various investigators have studied the rate of iron oxidation and have generally concluded that the rate of ferrous iron oxidation is of the first order with respect to the ferrous iron concentration and the partial pressure of oxygen. JUST (1908) postulated that the rate was first order with respect to ferrous iron and oxygen and second order with respect to CO_2 as shown in the following relationship:

$$-\frac{d\left[Fe(HCO_3)_2\right]}{dt} = K.\ \frac{\left[Fe(HCO_3)_2\right]\left[O_2\right]}{\left[CO_2\right]^2} \qquad (16)$$

He further stated the relationship between the rate and pH as shown below:

$$-\frac{d\left[Fe^{++}\right]}{dt} = K.\ \frac{\left[Fe^{++}\right]\left[O_2\right]}{\left[H^+\right]^2} \qquad (17)$$

Where K is the overall rate constant for a typical set of experimental runs.

He concluded that the rate of oxidation of ferrous iron increased with HCO_3^- ion concentration, but decreased with concentration of free CO_2.

STUMM and LEE (1961) established on equation for the kinetics of oxidation of ferrous iron in their work with highly alkaline solutions:

$$-\frac{d\left[Fe^{++}\right]}{dt} = K\left[Fe^{++}\right]\left[O_2\right]\left[OH^-\right]^2 \qquad (18)$$

They have shown that oxidation of ferrous iron should be expected to occur rapidly in well-oxygenated water at pH values exceeding 7.2. Another study of catalytic effects on the rate of oxidation by certain anions and cations indicated that addition of trace amounts of Cu^{++}, Mn^{++}, Co^{++} and $H_2PO_4^-$ would hasten the rate of oxidation of ferrous iron, as shown in Fig.4.

Redox potential (E_h) measurements of a water express the net effect of all oxidizing and reducing constituents. The presence or absence of substances affecting E_h in ground water might also influence ferrous equilibria conditions and the kinetics of iron oxidation.

<u>Coagulation and Sedimentation of Insoluble Iron</u> In the pH range of 6 to 9, which occurs in natural waters having alkalinity values between 400 mg/l and 500 mg/l as $CaCO_3$, it is possible to precipitate bivalent iron as $FeCO_3$ along with the more common trivalent form, $Fe(OH)_3$. GHOSH and others (1966) found that, in central Illinois ground waters, the rate of iron precipitation was governed by the alkalinity and pH of the water as shown by the following relationship:

$$T_{\frac{1}{2}} = 522-0.33\times10^{14}\left[OH^-\right]^2 - 183.\log\left[A\right] \pm 8.10 \qquad (19)$$

where $T_{\frac{1}{2}}$ = half-life in minutes or time required for one-half of the ferrous iron in solution to be precipitated

OH^- = molar concentration of hydroxyl ion

A = alkalinity in mg/l as $CaCO_3$.

This relationship was derived from a regression analysis of the data obtained from their field studies and is shown on Fig.3. The ferric iron formed as a result of the oxidation of ferrous iron is hydrolyzed according to the equation.

$$2\,Fe^{++} + 2OH^- + (x+1)\,H_2O \rightarrow Fe_2O_3.xH_2O\downarrow + 2H^+ \qquad (20)$$

The insoluble hydrated ferric oxide can exist in two forms, namely the sol form, which is stable, and the floc form, which is unstable. Sol particles can grow to larger agglomerates, which become floc, and both forms will be present after hydrolysis. It is apparent, however, that flocculated particles are more easily filtered than sol particles, GHOSH (1965) gave the following sources of interference in the removal of iron by aeration and sedimentation :

1. the formation of solution hydroxo-polymers of aquo-bases of iron,
2. the formation of colloidal dispersions with organic colloids,

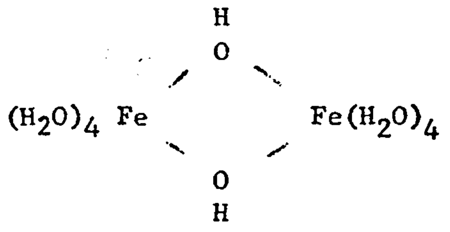
and 3. the formation of soluble chelates with organic sequestering agents.

The basic step in the formation of hydroxo polymers of any metal is a stepwise hydrolysis. For ferrous iron, the most common hydrolysis products that may exist in natural waters are

$\left[Fe(H_2O)_6\right]^{++}$, $\left[Fe(H_2O)_5(OH)\right]^{+}$, $Fe(OH)_2$ and $\left[Fe(H_2O)_3(OH)_3\right]^{-}$.
For ferric iron, the most common hydrolysis products are $FeOH^{++}$, $Fe(OH)_2^{+}$, $Fe(OH)_3$, and $Fe(OH)_4^{-}$ and it was found that aquo-ferric ion has far more affinity toward hydrolysis than the aquo-ferrous ion. Ferric hydroxo complexes have been known to polymerize as shown by the reaction:

$$2\left[Fe(H_2O)_5\ (OH)\right]^{+} = \left[Fe_2(H_2O)_8(OH)_2\right]^{4+} + 2H_2O \qquad (21)$$

It has been shown that iron atoms are bound by dihydroxy bridges in the polymer state. The probable structure for the above dimer is :



Thus, metastable colloidal iron hydroxo-polymers are formed through hydrolysis and polymerization. In the acid to neutral pH range, positively-charged colloidal ferric oxide is formed, while in the alkaline range negatively-charged colloidal ferric oxide prevails. In more concentrated solutions, the tetrapositive dimer is the predominant product of polymerization.

The positively-charged ferric oxides are hydrophobic in nature and may be stabilized by a coating of hydrophilic negatively-charged colloids in natural waters. They would thus carry a net negative charge. Perikinetic coagulation of such colloids may be effected by reducing the zeta potential. This can be done by destabilization of the sol with multivalent ions or colloids of opposite charge to that on the sol. The mechanism of this destabilization is mainly by an exchange reaction of the type shown below, with a resultant increase in pH :

$$\left[Fe_m(OH)_n\right]^{+x} + SO_4^{-2} = \left[Fe_m(OH)_{n-1}\ SO_4\right]^{x-1} + OH^- \qquad (22)$$

The above ion may form a complex with colloidal ferric oxide hydrate. However, a certain degree of adsorption of such ions on the colloids may be expected. Once the sol is destablized, flocculation is then initiated, resulting in gravity sedimentation of the insoluble iron.

RIDDICK (1961) reported that a zeta-potential of ± 5 milli-volts was optimum for the removal of all naturally occurring colloids, including those of iron. In order to attain such low potentials, the alkalinity in the water should be slightly in excess of that stoichiometrically required to react with coagulant, and he suggested the use of a coagulant dosage sufficient to lower the zeta-potential to - 10 milli-volts, provided that at least 6 to 8 mg/l of alkalinity remained. A suitable coagulant aid or cationic polyelectrolyte is then added to raise the potential to zero.

Many papers, such as SHAPIRO (1964), and CONNELLEY (1958), have been published describing difficulties in iron removal from water having a high content of organic matter. Some investigators have proposed that the iron or some part of the total iron content does not flocculate because it is organically chelated. Another theory is that the colloidal organic matter acts as a protective agent in regard to flocculation of the iron. However, it is generally agreed that destabilization of such colloidal organic matter can sometimes be achieved by a slight pH adjustment.

Temperature has significant effects upon iron removal. Once an iron-containing floc particle is formed, its rate of sedimentation is influenced by the temperature of the water. Increasing temperature reduces the viscosity of the water and thus improves settling, provided that precautions are taken to avoid convection currents which would disturb the process. STUMM and LEE (1961) showed that the rate of iron oxidation was also retarded significantly at low temperatures.

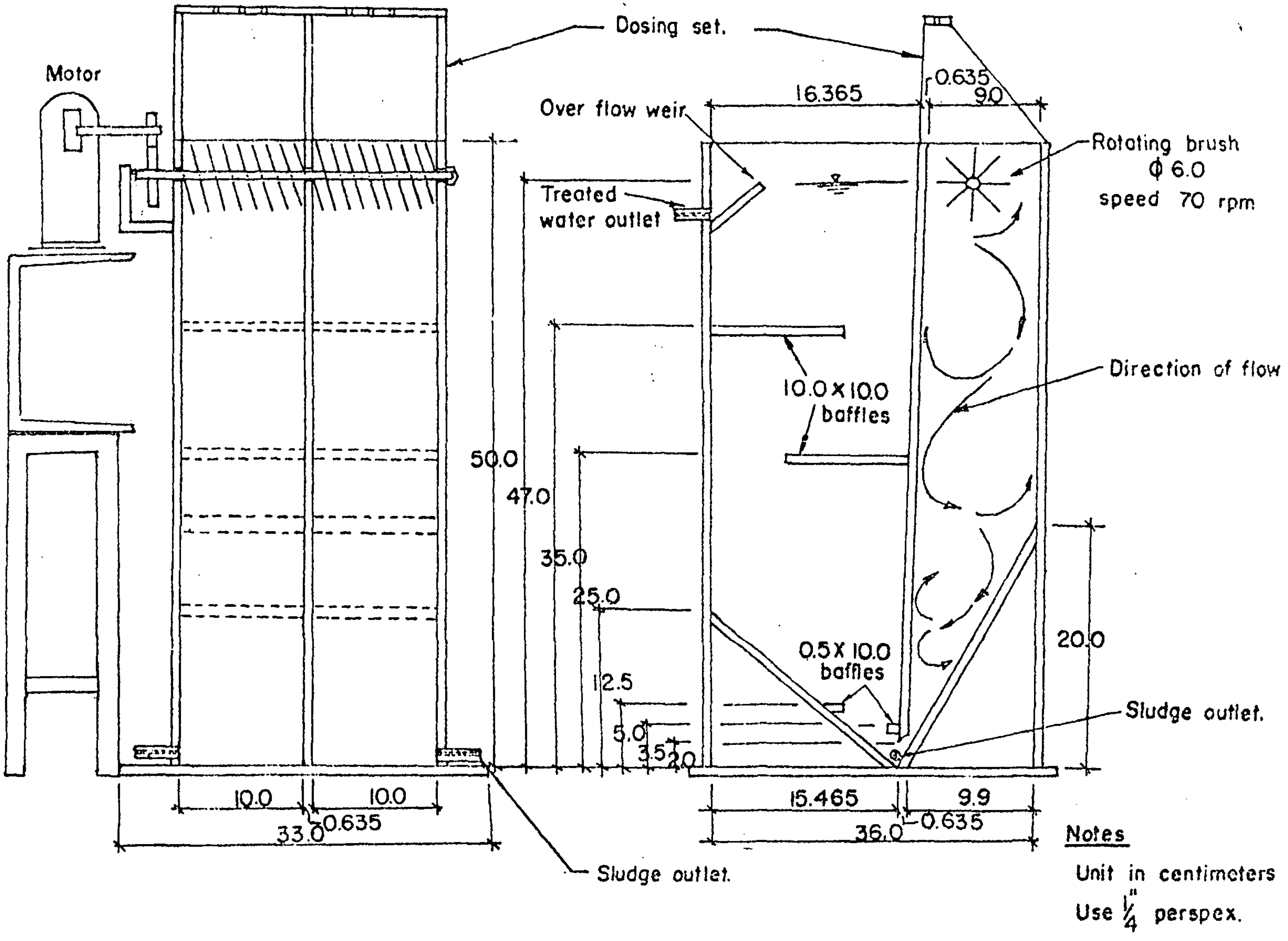
IV EXPERIMENTAL INVESTIGATIONS

Operation of Laboratory - Scale Iron Removal Unit

Fig.12 and 13 show a schematic diagram and photograph of two parallel laboratory-scale iron removal units. Each unit was composed of two compartments to simulate a flocculation basin and a sedimentation basin. In the flocculation basin, a rotating brush was installed and this was driven by an electric motor at a speed of 70 rpm. The rotating brush provided aeration, rapid mixing, and flocculation in the initial basin. The sedimentation basin had baffles to retard the upward flow of floc particles from the flocculation basin and to reduce short-circuiting of the flow in the sedimentation basin compartment.

The unit was designed on the basis of the upflow solids-contact process. Through the use of baffles, the insoluble hydrated ferric oxide precipitate formed in the aeration and flocculation process was made to pass downward through the opening between the bottom of the flocculation basin and the sedimentation basin. The water then flowed upward in the sedimentation basin and the floc gradually accumulated at the bottom of the basin.

According to the A.W.W.A. (1951) committee and BOND (1961), who studied the upflow solids-contact basin process employed in coagulation of water softening, dosed water from the mixing basin is first brought into intimate contact with a relatively large quantity of very small older particles at a high concentration. The presence in the early stages of large members of nuclei will



Notes

Unit in centimeters

Use 1/4" perspex.

Fig. 12 - Schematic Diagram of Laboratory - Scale Iron Removal Unit.

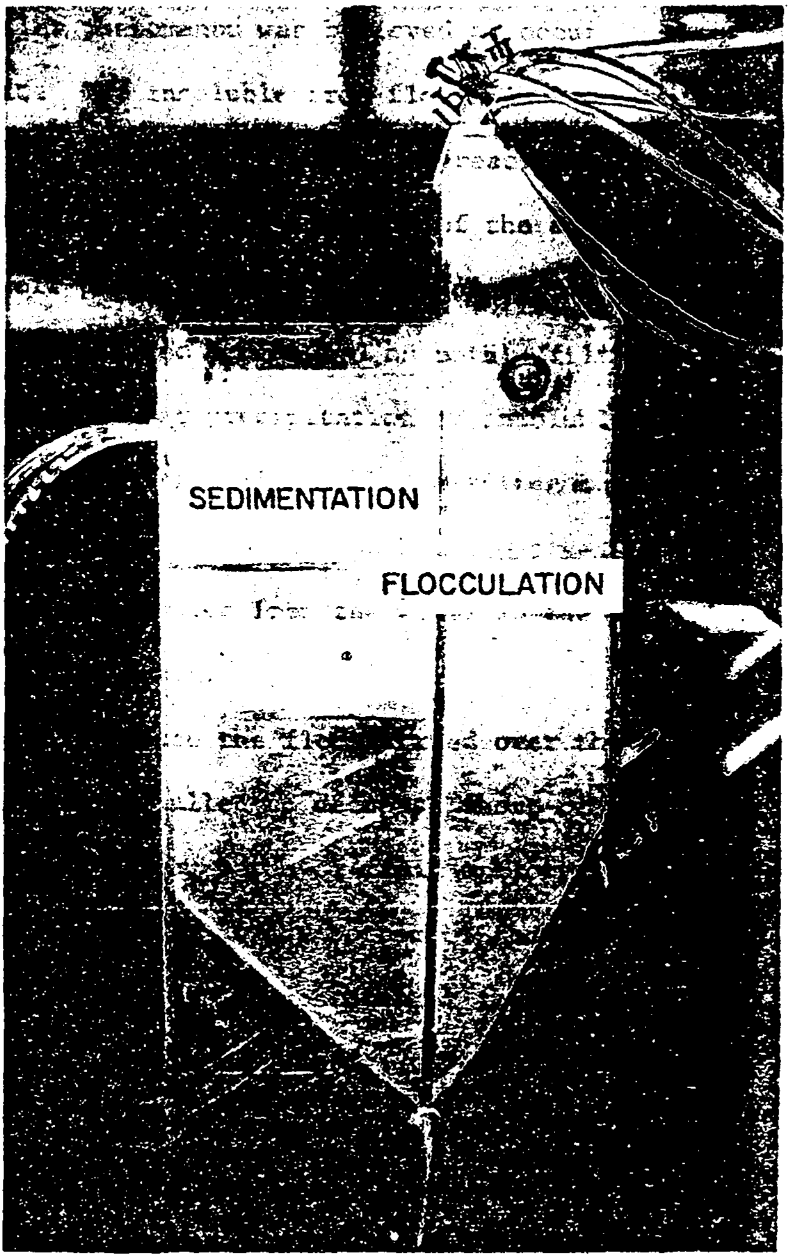


Fig. 13 - Laboratory-Scale Iron Removal Unit

encourage the solute, in a supersaturated solution to crystalize - out as a solid precipitate. In the latter stage, in the presence of large particles, further precipitation and agglomeration of the solids will occur until their removal is nearly completed.

A similar phenomenon was believed to occur in this iron removal unit. The insoluble iron floc flowed downward to the bottom of the sedimentation basin, it reacted with previously formed floc, resulting in a trapping of the solid impurities prior to their passing up to the effluent overflow weir. The previously formed floc functioned as both a filter and catalytic agent inducing greater precipitation of insoluble iron. As the cross sectional area of the sludge filter zone increased, the velocity of the upward flow of the water decreased, and precipitated particles separated from the water in the upper portion of the sedimentation basin.

In order to reduce the floc carried over the overflow weir, two baffles were installed to decrease short-circuiting and retard the formation of narrow paths of rapid upflow velocity. Two small baffles were also fixed at the bottom of the sedimentation basin to lengthen the path of the dosed water in passing through the fluidized bed of pre-formed sludge.

The raw iron-bearing ground water flowed by gravity from the reservoir to the flocculation basin in which the rotating brush provided dissolved oxygen to oxidize the soluble ferrous iron into insoluble ferric precipitate as shown by Eq. 6.

$$4Fe^{++} + (2x + 4)H_2O + O_2 \rightarrow 2Fe_2O_3.xH_2O\downarrow + 8H^{+} \qquad (6)$$

Aeration from the rotating brush was found to be insufficient to remove the original free carbon dioxide and the additional carbon dioxide resulting from the above reaction. Sodium hydroxide (NaOH) was therefore added to neutralize the CO_2 and to raise the pH to above 8.0 in order to improve the formation insoluble ferric hydroxide floc and thus hasten the precipitation rate.

Design of Experiments

The study was carried out in three steps, the first of which was to prepare, from a natural ground water, a high iron-bearing water from which the iron would neither precipitate nor settle out of solution during the course of the study. Secondly, preliminary investigations with jar tests were performed to determine the optimum pH range and the optimum dose of coagulant aid for iron removal from the prepared water. Finally, treatment of the prepared water in a simply designed laboratory-scale iron removal unit was carried out, according to the information obtained on the jar tests, to determine its efficiency.

Ferrous sulfate ($FeSO_4.7H_2O$) was added to provide a high soluble iron concentration in the natural ground water. In order to maintain the natural condition of the ground water, as it would be when being drawn from a well, the sample to be treated was stored in a closed reservoir devoid of oxygen.

The effect of pH and coagulant aids on iron removal were studied with jar tests prior to operation of the laboratory-scale unit. Sodium hydroxide was chosen for pH adjustment because of its strong alkalinity, compared with soda ash (Na_2CO_3), and slaked lime $Ca(OH)_2$, and its high solubility. Only a small amount of 0.1 N. NaOH was found to give satisfactory pH control in the unit. The coagulant aids used were organic high molecular cationic, anionic, and nonionic polyelectrolytes, and Bangkok clay. Four runs were made on the laboratory - scale unit. During the first run, the pH of the water was controlled and there was no addition of coagulant aid. The remaining three runs were carried out with coagulant aids.

Analyses of the following water characteristics were made throughout the course of experiments:

pH,
Alkalinity,
Dissolved Oxygen (D.O.),
Free carbon dioxide (CO_2),
Hardness,
Ferrous iron (Fe^{++}), and
Total iron

Materials and Equipment

Fig.14 and 15 show the arrangement of the laboratory-scale system, which consisted of two parallel units. Each unit was composed of a closed reservoir, and an iron removal plant.

Ground water reservoir - A closed reservoir with inside dimensions of 40 cm (15.7 in) in width, 60 cm. (23.6 in) in length and 40 cm. (15.7 in) in height was made of perspex sheet 9.53 mm. (3/8 in) thick. The total volume of the reservoir was 96 liters.

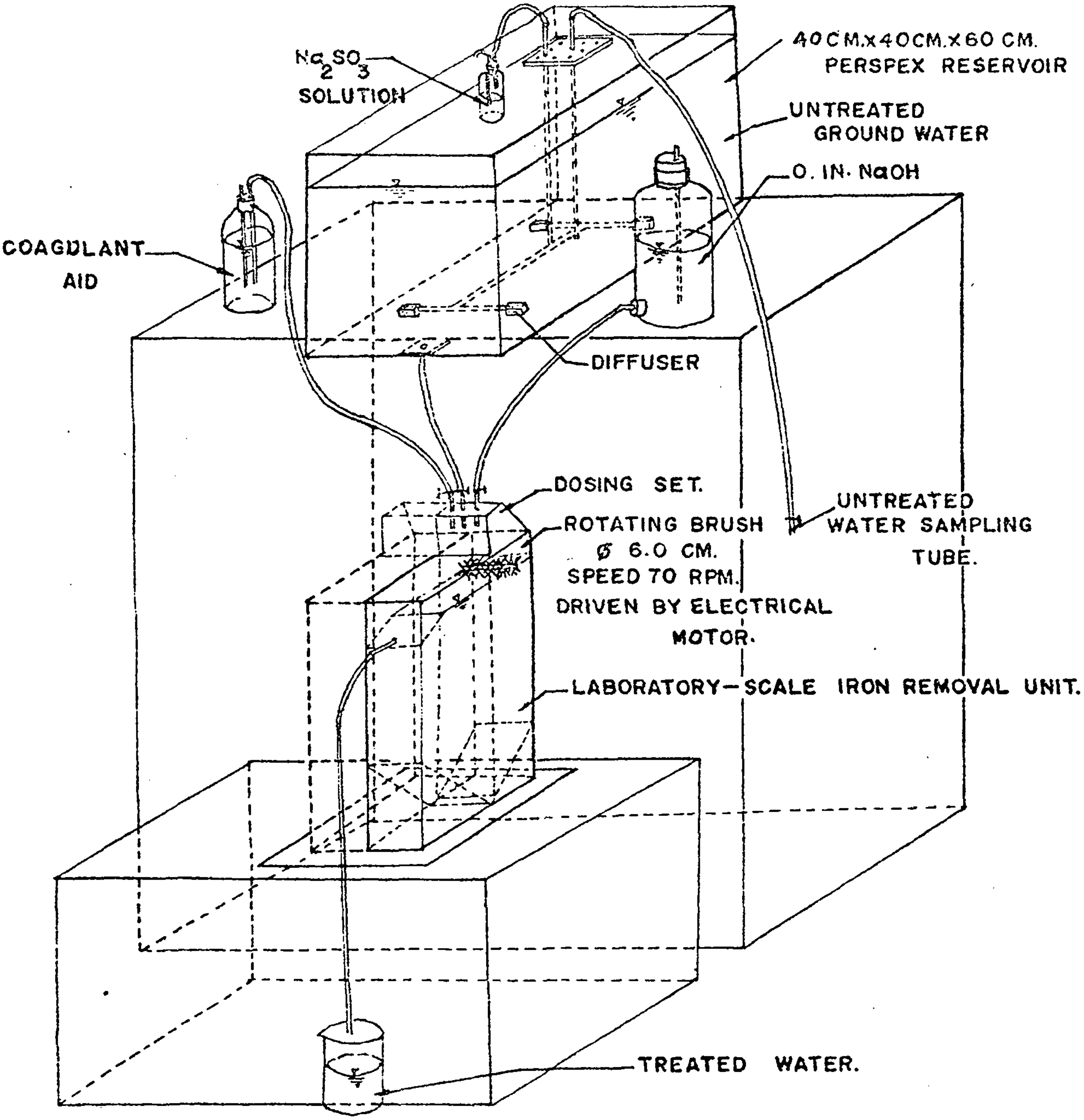


FIG. 14 – SCHEMATIC DIAGRAM OF ARRANGEMENT OF LABORATORY-SCALE IRON REMOVAL SYSTEM.

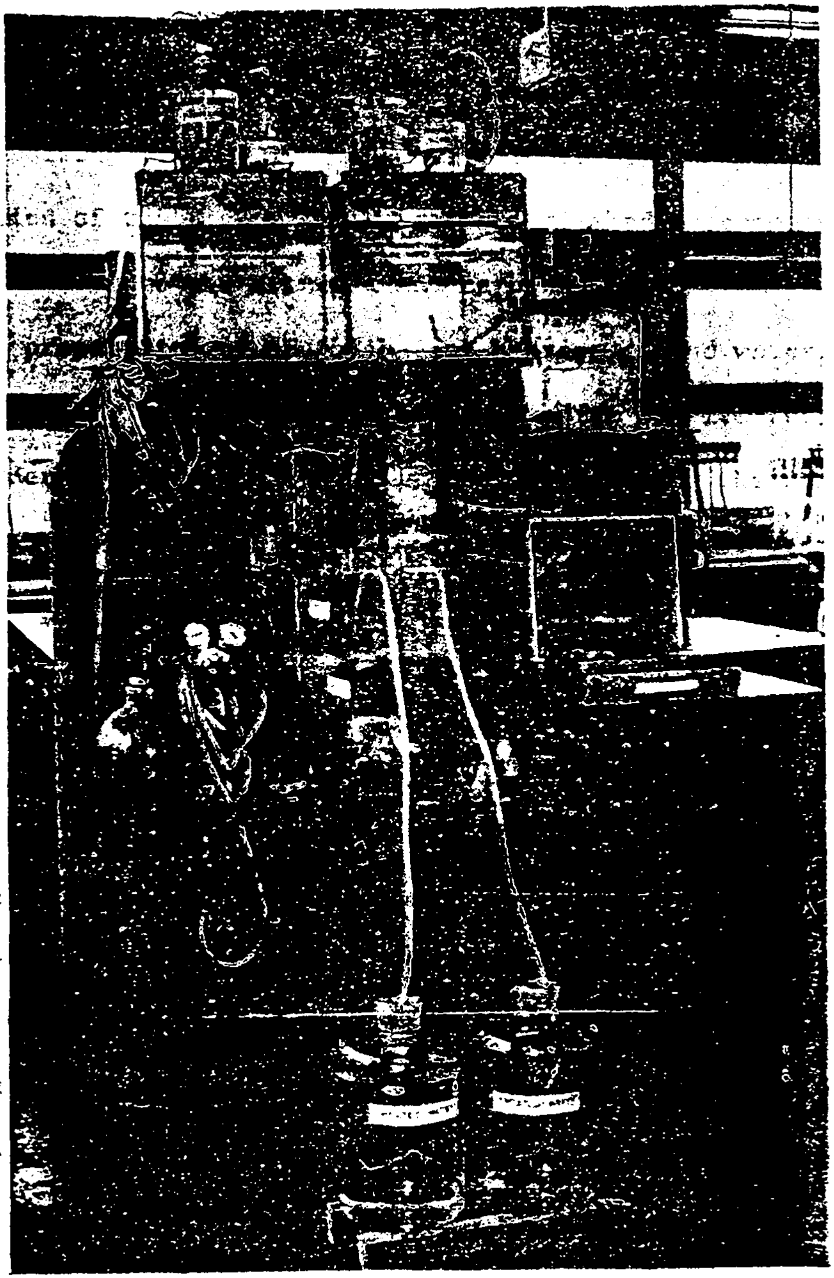


Fig. 15 - Arrangement of Laboratory-Scale Iron Removal System.

At the bottom of the reservoir, an outlet perspex tube 0.2 cm (0.08 in) inside diameters could be inserted. The lower end of the 1-mm. tube was connected to four diffusers, and the upper end was connected to a plastic tube. During the preparation of high iron-bearing ground water, removal of dissolved oxygen and carbonation of the ground water was accomplished by connecting this plastic tube to the nitrogen and carbon dioxide tanks respectively. After preparation of the high iron-bearing ground water, the plastic tube was then connected to a sodium sulfite solution bottle in order to deoxygenate the air before entering the reservoir. Both the lower and upper ends of the 2-mm tube were connected to long plastic tubes in such a way that samples of untreated water could be taken when required.

Laboratory - scale iron removal unit - A schematic diagram and photograph of the laboratory-scale iron removal unit are shown in Fig.12 and 13. Each unit was made of perspex sheets 6.35 mm (¼ in.) thick and was 10 cm. (3.94 in) wide, 26 cm (10.43 in) long and had a total depth of 50 cm (19.7 in), including 3 cm (1.18 in) free-board. The net capacity was 9.78 liters. The unit was divided into a flocculation basin and a sedimentation basin, by a 10 cm.x 50 cm.(3.94 in. x 19.7 in.) perspex baffle. An opening of 2 cm.x 10 cm. (0.78 in. x 3.94 in.) at the bottom was provided to connect the two compartments. The unit was designed with a total detention time of 3 hours. This consisted of one hour in the flocculation basin, with a volume of 3.26 liters, and two hours in the sedimentation basin, with a volume of 6.52 liters. The influent flow rate, based on the three hour detention time, was 54.0 ml/min.

The flocculation basin consisted of a dosing arrangement at the top, a rotating brush and the basin. The rotating brush was made of a perspex shaft of 2.0 cm.(0.78 in.) diameter of the brush was 6.0 cm. (2.36 in.). The brush was rotated at a speed of 70 rpm by means of an electric motor.

The sedimentation basin contained an effluent overflow weir at the top, two baffles size 10 cm. x 10 cm. (3.94 in. x 3.94 in.) in the middle portion, and two small baffles size 10 cm.x0.5 cm. (3.94 in.x0.19 in.) at the bottom. The small baffles at the bottom helped to increase the distance the folcculated water had to pass through previously - formed floc, while the baffles in the middle portion, helped to retard short - circuiting and to prevent floc being carried over the overflow weir. At the lower end of the bottom, between the basins, was installed a sludge outlet tube.

Other materials required were a carbon dioxide gas tank for pH adjustment and a nitrogen gas tank for deoxygenation of the ground water in the reservoir. A 2.5-liter bottle was used for coagulant aid and a 10-liter bottle for sodium hydroxide. The solution of both coagulant aid and sodium hydroxide were fed by gravity with their rate of flow controlled by piezometer tube.

Procedure and Analytical Method

All chemical analyses of untreated and treated ground water, except for dissolved oxygen, were carried out according to the procedures gives in A.P.H.A., A.W.W.A., W.P.C.F.(1965), hereinafter referred to as STANDARD METHOD (1965). Determination of dissolved oxygen in the flocculation and sedimentation basins was made by means of a Precision Scientific Co., Galvanic Cell Oxygen Analyzer. pH measurement was made with a Richmond Analytical Pocket pH meter.

Preparation of high iron-bearing ground water - In order to keep the condition of soluble ferrous iron as exists in ground water prior to treatment the water was deoxygenated. The iron bearing ground water used in this study was taken from the artesian wells at Wat Nang and Wat Warurachin, Dhonburi. Table 3 shows the characteristics of the ground waters.

Table 3. Chemical Analyses of Ground Water from Wat Nang and Wat Warurachin, Dhonburi.

Determination	Wat Nang				Wat Warurachin
	Dec. 30, 66	Jan. 11, 67	Jan. 21, 67	Feb. 18, 67	Feb. 25, 67
pH	6.6	6.6	6.6	6.6	6.6
Total Hardness mg/l $CaCO_3$	639.0	588.0	052.0	632.0	556.0
HCO_3^- mg/l, $CaCO_3$	324.0	318.0	328.0	308.0	316.0
Total Fe,mg/l	2.84	3.20	2.54	2.65	2.56
Fe^{++} , mg/l	2.10	1.40	1.38	2.32	2.29
Free CO_2,mg/l	86.0	80.0	72.0	78.0	88.0
Dissolved Oxygen,mg/l	4.2	4.9	3.2	3.8	0.8
Temperature, °C	34.0	33.5	34.0	34.0	34.0

Reduction of dissolved oxygen in the ground water sample was first accomplished by bubbling nitrogen through the liquid for one hour, the excess gases being removed through the opening at the top of the reservoir, The residual dissolved oxygen was then removed by addition of anhydrous sodium sulfite (Na_2SO_3), 7.9 mg/l of Na_2SO_3 was required for 1 mg/l deoxygenation as shown by:

$$O_2 + 2Na_2SO_3 \rightarrow 2\,Na_2SO_4 \qquad (23)$$

The stock solution of 5 mg/ml of $FeSO_4.7H_2O$ was then added to the deoxygenated water to give 50 mg/l $FeSO_4.7H_2O$ and this was followed by carbonation for about one to two minutes to keep the pH at about 6.4 to 6.5. The excess carbon dioxide could again be stripped off by nitrogen gas. The perspex reservoir was then tightly closed by tightening bolts along the edges of the cover. Air flowing into the reservoir was deoxygenated in passing through the sodium sulfite bottle. Because this tube was connected to diffusers at the bottom, the tube also worked as head controller for the untreated ground water flow rate. Sampling of the untreated ground water during treatment was done through the another sampling tube.

Titration curve of the ground water - To estimate the amount of 0.1 N.NaOH required at various pH's of the high iron-bearing ground water in the jar tests and the flow rate of 0.1 N.NaOH required for pH control during operation of the laboratory-scale iron removal unit, a titration curve of 1 liter of the reproducible ground water containing 50 mg/l $FeSO_4.\ 7H_2O$ was developed as shown in Table 4 and Fig. 16.

Table 4. Data on Titration of One Liter of Ground Water with 0.1 N.NaOH.

Chemical Analysis of Ground Water

pH	6.4	
Hardness	652.0	mg/l as $CaCO_2$
HCO_3^- Alkalinity	312.0	mg/l as $CaCO_3$
Total Fe	11.80	mg/l
Fe^{++}	7.36	mg/l
Free CO_2	110.0	mg/l
Dissolved Oxygen	1.6	mg/l
Temperature	27.5	°C

Titration with 0.1 N. NaOH

pH	0.1 N.NaoH ml	pH	0.1 N.NaOH ml	pH	0.1 N.NaOH ml
6.4	0	7.8	32.0	9.1	53.8
6.6	3.0	7.9	32.8	9.2	57.8
6.7	10.2	0.0	33.2	9.3	65.2
6.8	15.7	8.1	34.6	9.4	69.2
6.9	16.2	8.2	35.7	9.5	77.0
7.0	18.1	8.3	36.2	9.6	82.0
7.1	23.4	8.4	38.4	9.7	89.8
7.2	24.8	8.5	40.0	9.8	92.5
7.3	25.6	8.6	41.0	9.9	107.0
7.4	27.2	8.7	43.0	10.0	113.0
7.5	28.9	8.8	47.5	19.1	117.0
7.6	30.4	8.9	42.1	10.2	121.2
7.7	31.2	9.0	52.4		

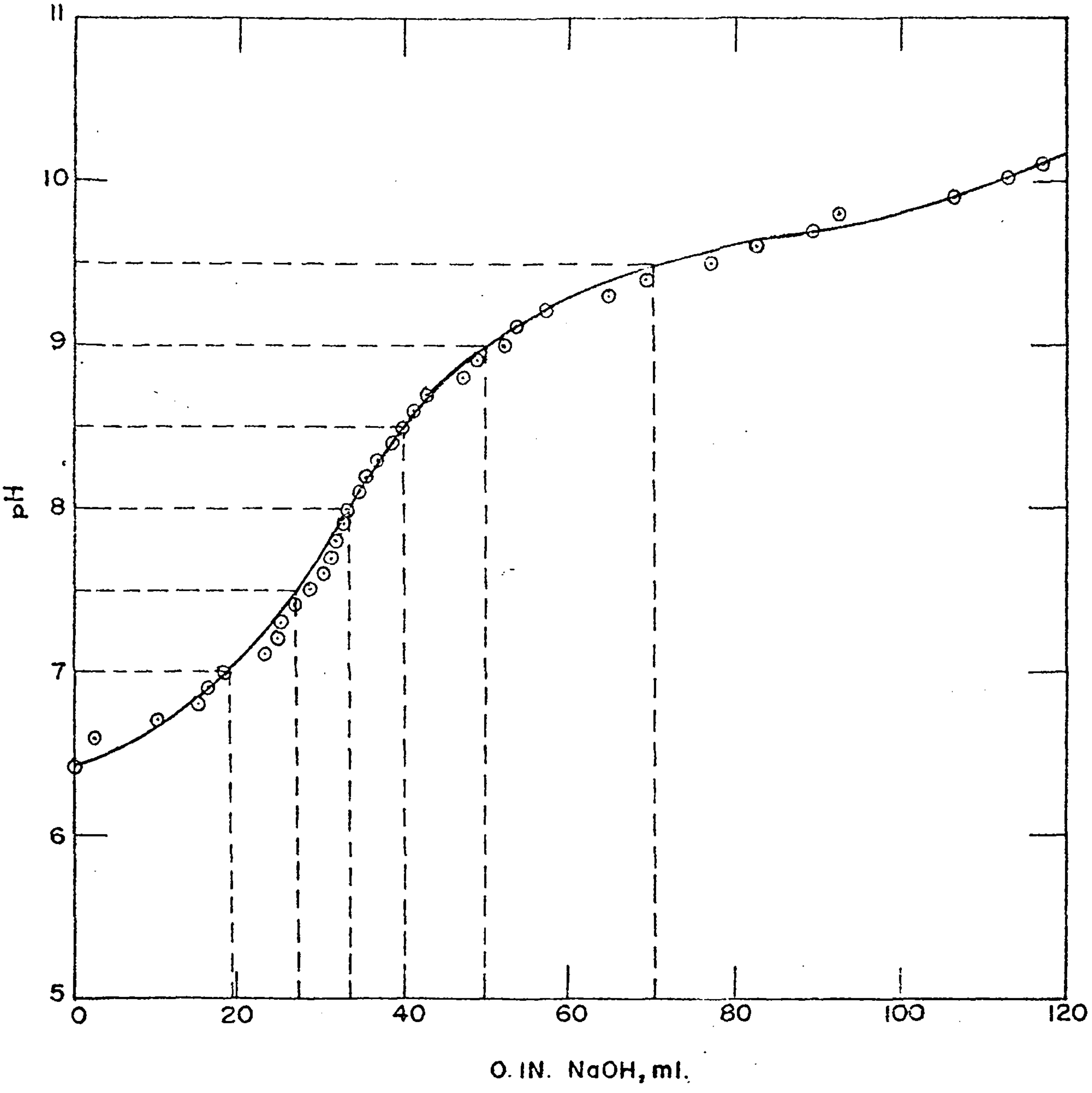


Fig. 16— Titration Curve of One Liter Ground Water v.s. O.I N. NaOH.

Jar tests The same reproducible ground water with 50 mg/l $FeSO_4.7H_2O$ was used in jar tests to determine an optimum, pH range and optimum coagulant aid dosages required for iron removal. In the jar tests, a series of six 1-liter beakers was set, each filled with one liter of the ground water. The 0.1 N. NaOH was added to give different pH's as required according to the titration curve obtained earlier. The contents were consecutively mixed with a paddle speed of 70-80 rpm for 30 seconds and then with a paddle speed of 15 to 20 rpm for 30 minutes of flocculation time. After the flocculation period the beakers were allowed to stand for one hour and the upper portion of the supernatant was decanted into a suitable container and analysed immediately for alkalinity, total hardness, and total iron.

The jar test was first made to determine the optimum pH range for iron removal. The pH in each beaker was adjusted, using 0.1 N.NaOH, to pH's of 7.0, 7.5, 8.0, 8.5, 9.0 and 9.5. It was found that within the pH range of 8.0 to 8.5, there were some tiny floc particles in suspension at the end of settling time. Then a pH of 8.3 was selected to determine the optimum dose of coagulant aid.

In the determination of the optimum dose of coagulant aid, the ground water was kept at a pH of 8.3 using 0.1 N.NaOH before addition of coagulant aid at various doses. The range of coagulant aid dosage employed in each series of jar tests followed the recommendations given in the product manual.

The water was rapidly agitated for 30 seconds to disperse the coagulant aid throughout the body of the water with a paddle speed of 70-80 rpm and followed by 30-minute flocculation time. The paddle speed during the flocculation time was maintained at 15-20 rpm as before.

Determination of the optimum pH for the optimum amount of coagulant aid to obtain the most effective iron removal was then performed. The range of pH was started at its original pH and gradually increased to pH 7.0, 7.5, 8.0, 8.5 and 9.0 respectively. These optimum coagulant aid doses and optimum pH's were then used in the laboratory-scale iron removal unit.

Another study on coagulant aids was made using Bangkok clay. The Bangkok clay was added to the ground water to produce a series with 25,50,75,100 and 125 turbidity units, as measured by the Jackson turbidimeter. Stock solution of ferrous sulfate ($FeSO_4.7H_2O$) was then added to give a dose of 50 mg/l $FeSO_4.7H_2O$ in each beaker. The contents were mixed continuously with a paddle speed of 70-80 rpm for 30 seconds, followed by 30 minutes flocculation time with a paddle speed of 20-30 rpm. After the flocculation period the beakers were allowed to stand for two hours and the upper portion of the decanted supernatant was analyzed immediately for turbidity and iron. Another jar test with clay as coagulant aid was carried out using 25 mg/l $FeSO_4.7H_2O$. The use of clay as coagulant aid was not investigated with the laboratory - scale unit because of difficulties in the application of clay in suspension.

Experiments on the laboratory-scale iron removal unit The laboratory-scale iron removal unit was first tested for the efficiency of the rotating brush in providing dissolved oxygen to the ground water. Dissolved oxygen, temperature, and pH were recorded every 30 minutes up to the designed three hour detention time of the unit.

Four runs were made on the unit. The first run was operated with only pH control in the flocculation basin, the second run with pH control and FLOCCOTAN as coagulant aid, the third run with pH control and Nalco-600 as coagulant aid and the fourth run with pH control and PURIFLOC N-11. The dose of coagulant aid and the pH used in each run were based on the results obtained from the jar tests. The total flow rates of the ground water, sodium hydroxide, and coagulant aid were kept at 54 ml/min.

At the beginning of the treatment, the specially prepared ground water containing 50 mg/l $FeSO_4.7H_2O$ was used in order to accelerate the formation of insoluble iron floc at the bottom of the unit. It took about 24 hours of continuous feeding of this ground water to fill up the bottom opening with floc particles. Then, ground water with only 25 mg/l of $FeSO_4.7H_2O$ was passed through the unit until an effluent with constant characteristics was obtained.

Chemical analyses of untreated and treated ground waters and measurement of dissolved oxygen, temperature and pH in both flocculation and sedimentation basins were carried out from time to time.

V EXPERIMENTAL RESULTS AND DISCUSSION

Ground Water Characteristics

Table 3 shows chemical analyses of the ground waters from Wat Nang and Wat Warurachin in Dhonburi Municipality. The ground water from the well at Wat Nang was used from the beginning of the experiments up to run no.2, when it was found that the well had dried up. Thus, the ground water used for runs 3 and 4 was taken from the well at Wat Warurachin.

The characteristics of the ground water from Wat Nang varied from time to time. The total hardness varied from 598 mg/l to 639 mg/l as $CaCO_3$, total iron from 2.54 mg/l to 3.20 mg/l iron, ferrous iron from 1.40 mg/l to 2.32 mg/l iron and free carbon dioxide from 72 mg/l to 86 mg/l. Wat Nang water was found to be high in dissolved oxygen, in the range of 3.2 to 4.2 mg/l, compared with the well water from Wat Warurachin, at 0.8 mg/l. This had an effect on the ferrous iron content of the ground water. Total iron present in the ground water from Wat Warurachin was mainly in the ferrous form. The temperature of the ground water from both wells was relatively high in the range of 33.5°C to 34.0°C. The total hardness of the ground waters from both wells was found to be very high also, being 556 mg/l at Wat Nang and 652 mg/l (as $CaCO_3$) at Wat Warurachin. SAWYER (1960) classified waters with a total hardness greater than 300 mg/l as $CaCO_3$ as very hard.

Preliminary Investigations

Treatment with NaOH. Table 5 shows the characteristics of the ground water used in the jar tests. After modification it had high total iron of 11.8 mg/l with 7.36 mg/l of ferrous iron, high free crabon dioxide of 110 mg/l, bicarbonate alkalinity of 312 mg/l as $CaCO_3$, total hardness of 652 mg/l as $CaCO_3$ and temperature of 27.5°C.

A jar test was first conducted to determine the optimum pH for iron removal. The results shown in Table 6 indicate effective iron removal in the pH range of 8.5 to 9.0. The reactions involved when NaOH was used for pH adjustment and also as coagulant for the ground water might be explained as follows: First, ionization of NaOH increased the OH^- ion concentration in the solution according to the following equation:

$$NaOH \rightleftarrows Na^+ + OH^- \qquad (24)$$

These OH^- ions then neutralized the free CO_2. SAWYER (1960) considered the neutralization of free CO_2 in the water to be taking place in two steps as follows:

$$2\,NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \qquad (25)$$

$$Na_2CO_3 + CO_2 + H_2O \rightarrow 2\,NaHCO_3 \qquad (26)$$

Oxidation of ferrous iron into insoluble hydrated ferric oxide by NaOH might follow the course described by SIENKO and PLANE (1961). When a base such as NaOH is added to a ferrous solution, a nearly white precipitate of ferrous hydroxide $Fe(OH)_2$, is formed.

$$Fe^{++} + 2OH^- \rightarrow Fe(OH)_2 \qquad (27)$$

Table 5 - Chemical Analyses of Ground Water used in Jar Tests.

Constituents	Before addition of $FeSO_4.7H_2O$	After ⊛ addition of $FeSO_4.7H_2O$ and followed by carbonation
pH	6.6	6.4
Hardness as mg/l $CaCO_3$*	652.0	652.0
HCO_3^- alk as mg/l $CaCO_3$	320.0	312.0
Total Fe, mg/l	2.54	11.80
Fe^{++}, mg/l	1.38	7.36
Free CO_2, mg/l	72.0	110.0
Dissolved Oxygen, mg/l	3.2	1.6
Temperature, °C	34.0	27.5

Notes

⊛ includes 50 mg/l $FeSO_4.7H_2O$ as supplement

* hardness as mg/l $CaCO_3$ by EDTA method

On exposure to air this $Fe(OH)_2$ turns brown, as it is oxidized to form hydrated ferric oxide, $Fe_2O_3.7H_2O$, which might simply be written as $Fe(OH)_3$, ferric hydroxide. The oxidation could be written as :

$$4\ Fe(OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3 \downarrow \qquad (28)$$

The hydrated ferric oxide is a slimy, red brown, gelatinous precipitate. The presence of hydrated ferric oxide in the solution causes cation hydrolysis. This can be written as :

$$Fe^{+++} + H_2O \rightleftharpoons Fe\ OH^{++} + H^+ \qquad (29)$$

The most common hydrolysis products of ferric ion, are $FeOH^{++}$, $Fe(OH)_2^+$, $Fe(OH)_3$, and $Fe(OH)_4^-$ which may be written in ferric hydroxo complex forms as $\left[Fe(H_2O)_5(OH)\right]^{++}$, $\left[Fe(H_2O)_4(OH)_2\right]^+$, $\left[Fe(H_2O)_3(OH)_3\right]$ and $Fe(OH)_4^-$ (GHOSH, 1965). These ferric hydroxo complexes polymerize through dihydroxy bridges in the polymer state. That is, the polymerization of two $\left[Fe(H_2O)_5(OH)\right]^{++}$ by two hydroxyl ions to become $\left[Fe(H_2O)_8(OH)_2\right]^{4+}$. The electrically charged ferric hydroxo complexes are known as ferric oxide sols. Due to Brownian movement, the positively-charged ferric oxide particles collide with one another , and coagulate to form a larger particle. These particles in collision with one another again, form yet larger particles which are so large that Brownian motion cannot keep them in suspension. The ferric oxide, which is not hydrolyzed, according to SIENKO and PLANE (1961) has great adsorption power for H^+ ions on the surface. A particle which has H^+ adsorbed to it has a net positive charge and thereby repels any similarly charged particle.

Perikinetic coagulation of such electrically charged particles might be effected by reducing the zeta-potential. This can be done by destabilization of the sol with multivalent ions or colloids of opposite charge to that on the sol. Once the sol is destabilized, flocculation is then initiated and this results in gravity sedimentation of the insoluble iron.

The mechanism of destabilization of metastable ferric hydroxo polymers of this investigation can be considered as being mainly due to OH^- and $SO_4^=$ ions. The OH^- ions result from dissociation of NaOH as shown in Eq. 24. $SO_4^=$ ions are derived from the addition of $FeSO_4.7H_2O$, chemical deoxygenation by Na_2SO_3 to form Na_2SO_4 as shown in Eq. 23, and the chemical reaction of calcium nonalkaline hardness removal as shown in Eq.32.

The mechanism of the destabilization by $SO_4^=$ ions has been explained by GHOSH (1965) as :

$$\left[Fe_m(OH)_n\right]^{+x} + SO_4^{-2} = \left[Fe_m(OH)_{n-1}(SO_4)\right]^{x-1} + OH^- \qquad (30)$$

This reaction gives rise to the formation of a complex with colloidal hydrated ferric oxide and an increase in pH.

Removal of total hardness by NaOH might be represented by the following equations:

$$Ca(HCO_3)_2 + 2NaOH \rightarrow CaCO_3\downarrow + Na_2CO_3 + H_2O \qquad (31)$$

$$CaSO_4 + Na_2CO_3 \rightarrow CaCO_3\downarrow + Na_2SO_4 \qquad (32)$$

Only calcium alkaline and calcium non-alkaline hardness is expected to be removed when the pH is controlled at 9.5 in the jar test. Removal of magnesium alkaline hardness, $Mg(HCO_3)_2$, and magnesium non-alkaline hardness, ie $MgSO_4$, as gelatinous magnesium hydroxide occurs at pH above 10.8 (SAWYER, 1960).

Table 6 gives chemical analyses of the ground water treated in jar tests at various pH's with NaOH and Fig.17 shows the results of total iron removal. It appears that efficient iron removal is obtained in the pH range 8.5 to 9.0. No significant increase in total iron removal as a percentage ot total hardness removal occurred at pH values higher than 9.5. HCO_3^- alkalinity of the finished water is noted to increase, which might be due to neutralization of free CO_2 as shown in Eq. 25 and 26. Total hardness removal is observed to be related to total iron removal, being relatively low at low pH and rather high at high pH. The reactions occurring may be represented by Eq. 31 and 32. At lower pH's of 7.0 to 7.5, the supernatant was observed to be yellow-brown in color, which is the characteristic of the positively-charged ferric oxide. The dispersion of positively-charged ferric oxide in the supernatant was gradually decreased at a pH of 8.0 and nearly disappeared at pH 9.0 and 9.5. At higher pH, higher concentration of OH^- ions resulted in further reduction of positive charges on the surface of the ferric sols and neutralization of H^+ ions by the OH^- ions. This caused a reduction in the magnitude of zeta-potential so that repulsive forces between particles were less than the inter-particle attractive force or Van der Waal's force. Thus, coalescence of colloidal hydrated ferric oxide particles occurred and coagulation was accomplished.

Removal of total hardness was found to be significant

Table 6 - Chemical Analysis of Ground Water in Jar Tests at various pH's

Jar No	pH	Floc formation	Chemical Analyses After 1 - hour Settling Time					
			Alkalinity: mg/l as $CaCO_3$		Total Hardness mg/l as $CaCO_3$		Total Iron mg/l	
			HCO_3^-	$CO_3^=$	Residual	% Removal	Residual	% Removal
1	7.0	poor	354.0	-	620.0	4.9	7.60	35.6
2	7.5	fair	363.0	-	605.0	7.2	6.40	45.8
3	8.0	fair	425.0	-	598.0	8.3	1.24	89.4
4	8.5	fair	414.0	16.0	518.0	20.5	0.76	93.5
5	9.0	good	418.0	28.0	436.0	33.1	0.34	97.1
6	9.5	good	312.0	136.0	302.0	54.0	0.31	97.4

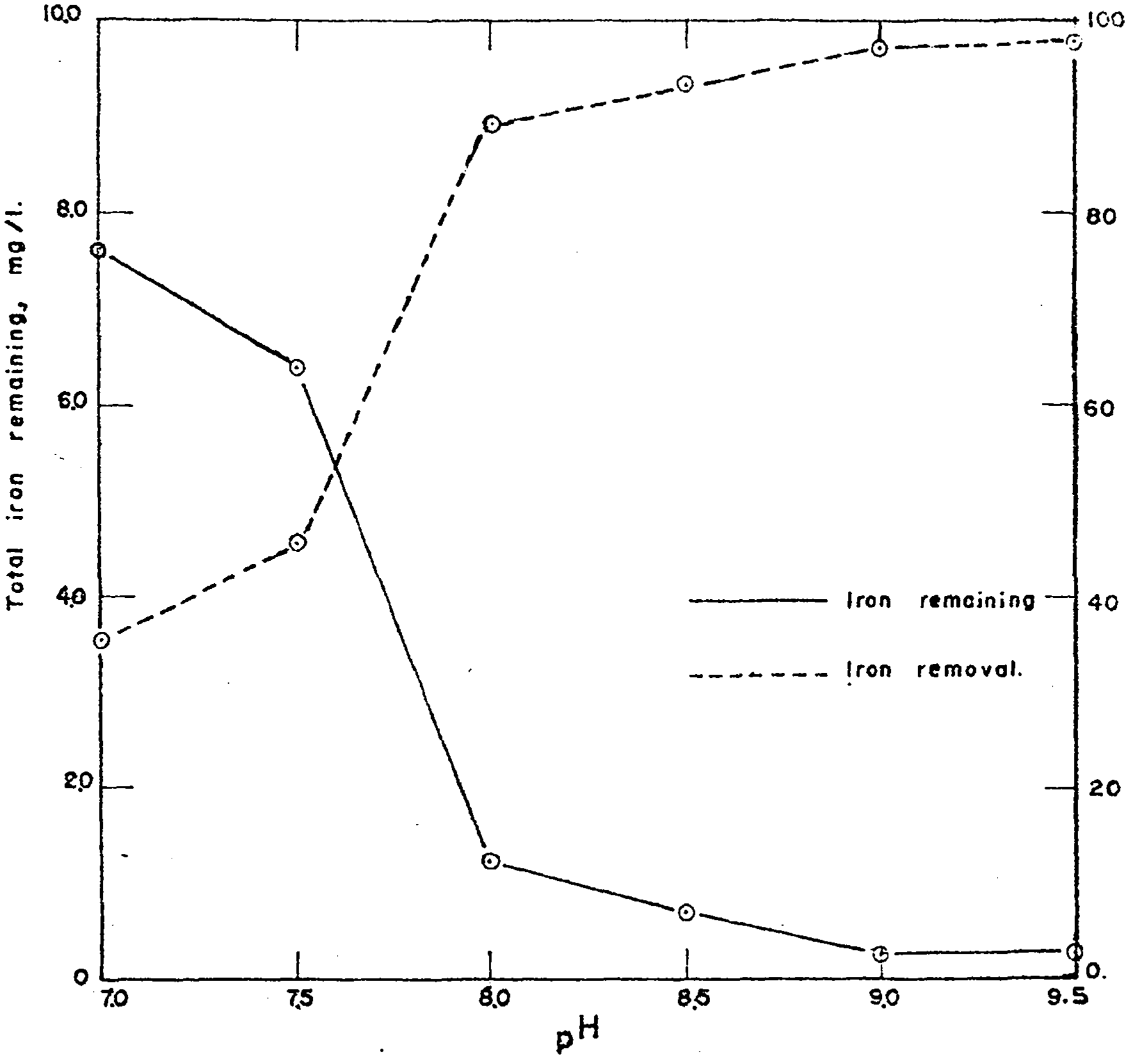


Fig. 17 - Iron Removal at Various pH's with NaOH Treatment.

at pH's between 8.5 and 9.5. At a higher pH, OH^- ions would first neutralize the free CO_2, as shown in Eq. 25 and 26, then oxidized the ferrous iron, as shown by Eq. 27 and 28. The excess OH^- ions still further neutralize the calcium alkaline and calcium non-alkaline hardness to form $CaCO_3$ precipitates, as shown by Eq. 31 and 32. Floc formation was observed to be highly improved at pH's above 8.5, which might be due to the presence of $CaCO_3$ precipitates. The $CaCO_3$ precipitates, according to FAIR and GEYER (1954), are negatively-charged and are heavier than ferric oxide particles. These $CaCO_3$ precipitates could provide nuclei for the ferric oxide and thus stimulate floc formation.

Treatment with coagulant aid. To determine the efficiency of commercial organic high molecular weight polyelectrolytes as coagulant aids for improving iron removal, the optimum dose of the electrolyte was first determined at pH 8.3. This was because it was found that at pH 8.0 and pH 8.5, there were still some suspended gelatinous precipitates in the supernatant water. It was thought that this might be improved by the addition of polyelectrolyte. MINZ (1964) stated that the use of polyelectrolytes as coagulant aids had not been reduced to an exact science. The exact chemical nature of the commercial polyelectrolytes employed in this investigation was not known.

Improvement of hydrated ferric oxide flocculation with anionic polyelectrolyte at pH 8.3 might be due to electrolytic dissociation of the polyelectrolyte to give large highly negatively-charged polymeric ions. Anionic polyelectrolyte molecules consist of separate chains cross-linked with stable chemical bonds which dissociate in water to give negatively-charged macroions (MINZ, 1964). The presence of negatively-charged metastable colloidal iron and the gentle movement provided during the flocculation period promote rapid flocculation. The separated chains cross-linked by stable chemical bonds of the polymer molecule also act as bridges between the entrapped colloidal particles, thus promoting larger floc formation.

Table 7 and 8 show the results obtained when the anionics PURIFLOC A-22 and FLOCCOTAN were used at pH 8.3. Floc formation was observed to be greatly improved and the flocs were no longer gelatinous. They were found to be dense, tough, and in larger and heavier forms. However, the tiny suspended ferric oxide flocs were still observed to exist in the supernatant when PURIFLOC A-22 was dosed at 2 mg/l. At a higher dose of 4.0 mg/l, the dispersion of tiny flocs was slightly increased. This might be due to the complete adsorption of negatively-charged polymeric ions onto the metastable colloidal ferric oxide stabilizing the suspension, thus inhibiting flocculation of these flocs.

Addition of FLOCCOTAN, a tannin-based polyelectrolyte, was more effective in iron removal than PURIFLOC A-22. Insoluble iron precipitates agglomerated to form larger and heavier dark brown particles of irregular shape. These flocs settled down rapidly even during flocculation. At doses of 5.0 mg/l and

Table 7 - Chemical Analyses of Ground Water on Jar Test with Purifloc A-22 as Coagulant Aid at pH 8.3

Jar No.	Purifloc A-22 mg/l	Floc formation	Chemical Analyses After 1-hour Settling Time			
			HCO_3^- mg/l as $CaCO_3$	Hardness mg/l as $CaCO_3$	Total Iron mg/l	
					Residual	% Removal
1	none	fair	424.0	574.0	0.82	93.0
2	0.5	fair	432.0	570.0	0.94	92.0
3	1.0	good	930.0	580.0	0.78	93.5
4	2.0	good	934.0	574.0	0.76	93.5
5	3.0	good	428.0	586.0	0.86	92.8
6	4.0	fair	932.0	582.0	1.02	91.4

Table 8 - Chemical Analyses of Ground Water on Jar Test with Floccotan as Coagulant Aid at pH 8.3

Jar No.	Floccotan mg/l	Floc formation	Chemical Analyses After 1-hour Settling Time			
			HCO_3^- mg/l as $CaCO_3$	Hardness mg/l as $CaCO_3$	Total Iron mg/l	
					Residual	% Removal
1	none	fair	428.0	572.0	0.85	92.6
2	2.0	fair	438.0	578.0	0.76	93.5
3	3.0	fair	437.0	582.0	0.52	95.5
4	4.0	good	440.0	579.0	0.40	96.5
5	5.0	good	438.0	582.0	0.22	98.0
6	6.0	good	439.0	580.0	0.24	98.0

6.0 mg/l, good flocs were formed with relatively small numbers of tiny suspended flocs in the supernatant. A dose of 5.0 mg/l was considered optimum for determination of the optimum pH for the FLOCCOTAN. Fig. 18 shows the comparison of iron removal at various pH's with anionic PURIFLOC A-22 and FLOCCOTAN. Table shows that higher pH values of 8.5 and 9.0 with 5 mg/l FLOCCOTAN gave a slight improvement in iron removal. An optimum pH range o of 8.5 to 9.0 at the optimum dose of 5 mg/l FLOCCOTAN gave slight improvement in iron removal. An optimum pH range of 8.5 to 9.0 at the optimum dose of 5 mg/l FLOCCOTAN would be suggested for use in the iron removal unit.

The reaction which occurs when nonionic polyelectrolyte is used as coagulant aid in the flocculation of hydrated ferric oxide might be due to the fact that the nonionic polyelectrolyte molecule is of elongated shape owing to the rigid linkages between the polymolecular chains afforded by oxygen atoms. The polymer can yield both large positive ions and large negative ions (MINZ, 1964). Hence, they can destabilize both positively-charged and negatively-charged ferric hydroxo polymers as well as $CaCO_3$ particles existing in the solution and result in improvement of agglomeration of these particles.

Table 10 and 11 present the chemical analyses of the ground water treated with nonionic PURIFLOC N-11 and N-17 at pH 8.3. Agglomeration of suspended iron precipitates was found to be markedly improved, as larger and heavier flocs were formed.

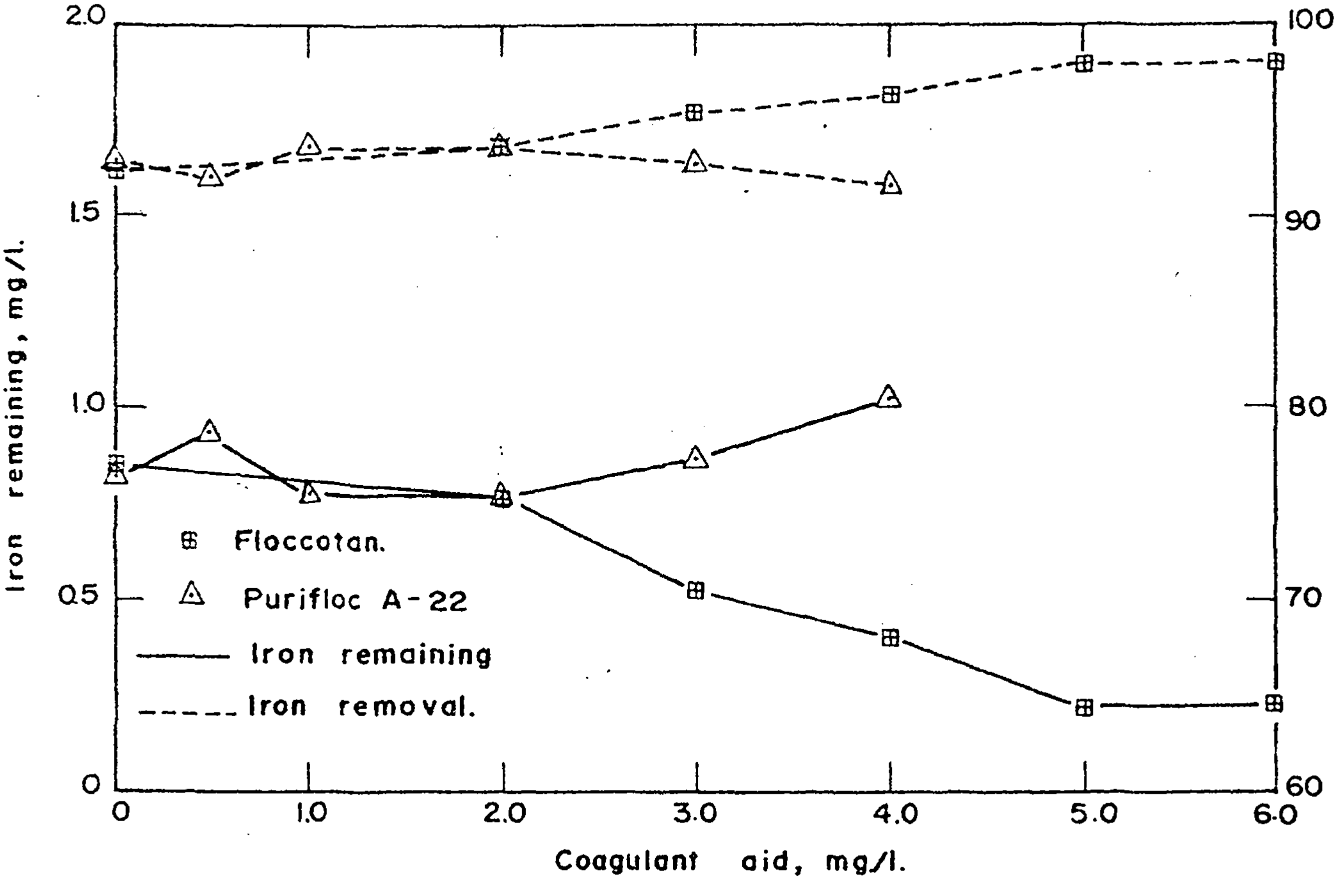


Fig. 18– Effect of Anionic Purifloc A-22 and Floccotan on Iron Removal at pH 8.3

Table 9 - Chemical Analyses of Ground Water on Jar Test with 5 mg/l Floccotan as Coagulant Aid at Various pH

Jar No.	pH	Floc formation	Chemical Analyses After 1-hour Settling Time				
			Alkalinity mg/l as $CaCO_3$		Hardness mg/l as $CaCO_3$	Total Iron mg/l	
			HCO_3^-	$CO_3^=$		Residual	% Removal
1	6.4	poor	324.0	-	650.0	9.80	17.0
2	7.0	poor	342.0	-	620.0	7.32	38.0
3	7.5	poor	360.0	-	614.0	3.72	68.5
4	8.0	fair	422.0	-	596.0	1.08	90.9
5	8.5	good	412.0	12.0	514.0	0.18	98.2
6	9.0	good	420.0	28.0	458.0	0.14	98.7

Table 10 - Chemical Analyses of Ground Water on Jar Test with PURIFLOC N-11 as Coagulant aid at pH 8.3

Jar No.	PURIFLOC N-11 mg/l	Floc Formation	Chemical Analyses After 1-hour Settling Time			
			HCO_3^- mg/l as $CaCO_3$	Hardness mg/l as $CaCO_3$	Total Iron mg/l	
					Residual	% Removal
1	none	fair	430.0	578.0	0.87	92.5
2	0.5	poor	428.0	572.0	1.35	98.5
3	1.0	fair	434.0	570.0	0.84	92.7
4	2.0	fair	436.0	576.0	0.81	92.8
5	3.0	fair	432.0	580.0	0.98	91.6
6	4.0	poor	428.0	570.0	1.72	85.4

Table 11 - Chemical Analyses of Ground Water on Jar Test with PURIFLOC N-17 as coagulant aid at pH 8.3

Jar No.	PURIFLOC N-17 mg/l	Floc-formation	Chemical Analyses After 1-hour Settling Time			
			HCO_3^- mg/l as $CaCO_3$	Hardness mg/l as $CaCO_3$	Total Iron mg/l	
					Residual	% Removal
1	none	fair	424.0	574.0	0.85	92.6
2	0.5	fair	432.0	570.0	0.98	91.6
3	1.0	fair	430.0	580.0	1.10	90.6
4	2.0	fair	434.0	574.0	0.80	93.1
5	3.0	fair	428.0	586.0	0.98	91.6
6	4.0	fair	432.0	582.0	1.04	91.3

Table 12 - Chemical Analyses of Ground Water on Jar Test with 2 mg/l Purifloc N - 11 as Coagulant Aid at Various pH

Jar No.	pH	Floc formation	Chemical Analyses After 1-hour Settling Time				
			Alkalinity as mg/l $CaCO_3$		Hardness mg/l as $CaCO_3$	Total Iron mg/l	
			HCO_3^-	$CO_3^=$		Residual	% Removal
1	6.4	poor	330.0	-	656.0	10.12	14.3
2	7.0	poor	342.0	-	632.0	7.42	37.1
3	7.5	poor	358.0	-	621.0	4.12	65.0
4	8.0	fair	432.0	-	596.0	1.34	88.6
5	8.5	fair	422.0	12.0	512.0	0.80	93.2
6	9.0	fair	416.0	30.0	473.0	0.78	93.4

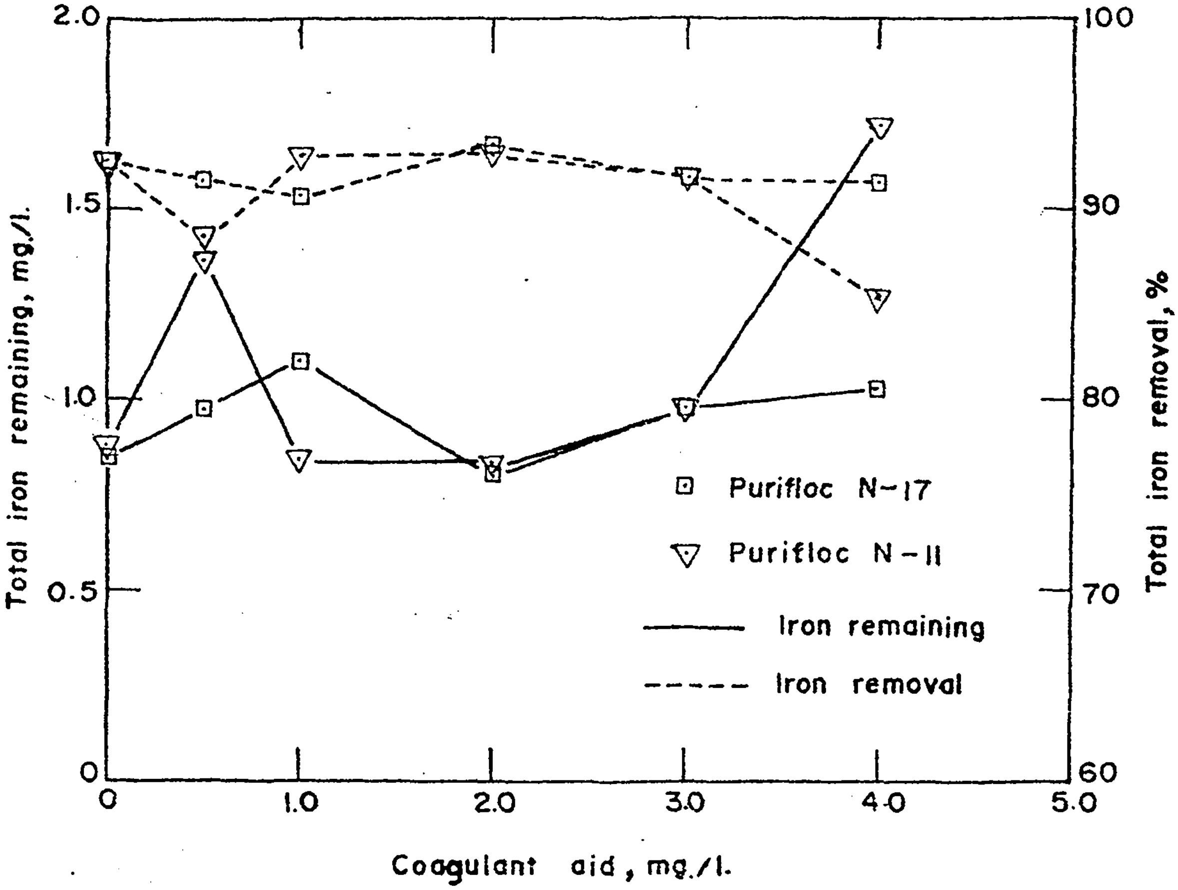


Fig. 19 - Effect of Nonionic Purifloc N-11 and N-17 on Iron Removal at pH 8.3.

The size of the flocs formed with both nonionic PURIFLOC N-11 and N-17 were generally smaller than the flocs formed by the anionic PURIFLOC A-22 and FLOCCOTAN. The tiny suspended iron particles still existed in the supernatant. Fig.19 shows the comparison of iron removal for PURIFLOC N-11 and N-17 at pH 8.3. The optimum dose of both PURIFLOC N-11 and N-17 was found to be 2 mg/l. At a higher dose of 4.0 mg/l, the dispersion of suspended particles was observed to be markedly increased. The floc formed with nonionic PURIFLOC N-11 was observed to be relatively large compared with those formed with nonionic PURIFLOC N-17. Table 12 shows that total iron removal could be improved at higher pH's of 8.5 and 9.0 with 2 mg/l nonionic PURIFLOC N-11 to a maximum of 93.4% iron removal at pH 9.0.

Addition of cationic polyelectrolyte to the ground water at pH 8.3 gave no improvement on total iron removal. Table 13 and 14 indicate that addition of both cationic Nalcolyte-605 and Nalco-600 at pH 8.3 interfered with floc formation. Total iron removal was slightly reduced compared with treatment using NaOH alone. This might have been due to the addition of positively charged polymeric ions interfering with the formation of the ferric oxide particles. Fig.20 shows comparison of iron removal between Nalco-600 and Nalcolyte-605 at pH 8.3. Table 15 gives chemical analyses of the ground water treated with 2 mg/l Nalco-600 at various pH's. Better total iron removal was obtained at higher pH values of 8.5 and 9.0.

Table 13 - Chemical Analyses of Ground Water on Jar Test with Nalcolyte - 605 As Coagulant Aid at pH 8.3

Jar No.	Nalcolyte 605 mg/l	Floc formation	Chemical Analyses After 1-hour Settling Time			
			HCO_3^- mg/l as $CaCO_3$	Hardness mg/l as $CaCO_3$	Total Iron mg/l	
					Residual	% Removal
1	none	fair	432.0	578.0	0.85	92.7
2	0.5	fair	442.0	580.0	1.20	89.9
3	1.0	fair	438.0	576.0	1.24	89.5
4	2.0	fair	437.0	578.0	1.07	91.0
5	3.0	fair	435.0	582.0	1.54	87.0
6	4.0	poor	440.0	574.0	1.92	83.6

Table 14 - Chemical Analyses of Ground Water on Jar Test with Nalco - 600 as Coagulant Aid at pH 8.3

Jar No.	Nalco-600 mg/l	Floc formation	Chemical Analyses After 1-hour Settling Time			
			HCO_3^- mg/l as $CaCO_3$	Hardness mg/l as $CaCO_3$	Total Iron mg/l	
					Residual	% Removal
1	none	fair	426.0	570.0	[illegible]	94.3
2	0.5	fair	440.0	578.0	[illegible]	90.3
3	1.0	fair	432.0	571.0	1.08	90.9
4	2.0	fair	438.0	582.0	1.02	91.2
5	3.0	fair	435.0	568.0	0.98	91.6
6	4.0	poor	422.0	583.0	1.88	84.0

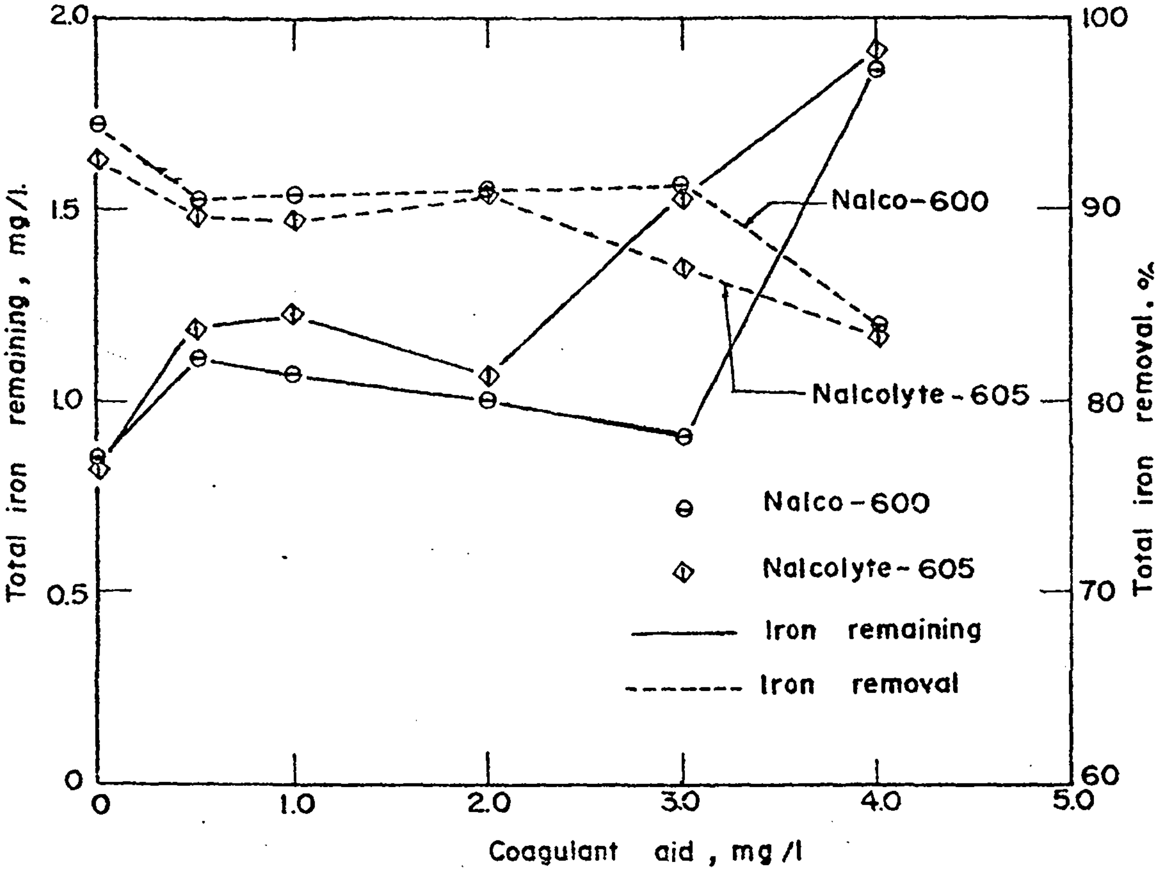


Fig. 20 - Effect of Cationic Nalco-600 and Nalcolyte-605 on Iron Removal at pH 8.3

Table 15 - Chemical Analyses of Ground Water on Jar Test with 2 mg/l Nalco - 600 as Coagulant Aid at Various pH

Jar No.	pH	Floc formation	Chemical Analyses After 1-hour Settling Time				
			Alkalinity as mg/l $CaCO_3$		Hardness mg/l as $CaCO_3$	Total Iron Time	
			HCO_3^-	$CO_3^=$		Residual	% Removal
1	6.4	poor	330.0	-	652.0	10.20	5.0
2	7.0	poor	341.0	-	628.0	8.54	27.5
3	7.5	poor	364.0	-	615.0	4.98	58.0
4	8.0	fair	428.0	-	597.0	1.85	84.3
5	8.5	fair	417.0	14.0	508.0	0.97	91.6
6	9.0	fair	422.0	32.0	462.0	1.03	91.2

The results of the jar tests indicated that HCO_3^- alkalinity of the finished water was increased. This was the result of neutralization of free CO_2 by NaOH as shown by Eq. 25 and 26. The addition of polyelectrolytes alone, without NaOH, did not have any effect on iron removal. The addition of various other types polyelectrolytes did not show any effect on iron removal, total hardness removal or change in bicarbonate alkalinity.

Fig. 21 shows that of the three types of polyelectrolyte used, FLOCCOTAN and the nonionic PURIFLOC N-11 seem to be more effective in assisting the removal of iron. During the jar tests, it was observed that floc formation was greatly improved when FLOCCOTAN and PURIFLOC N-11 were used.

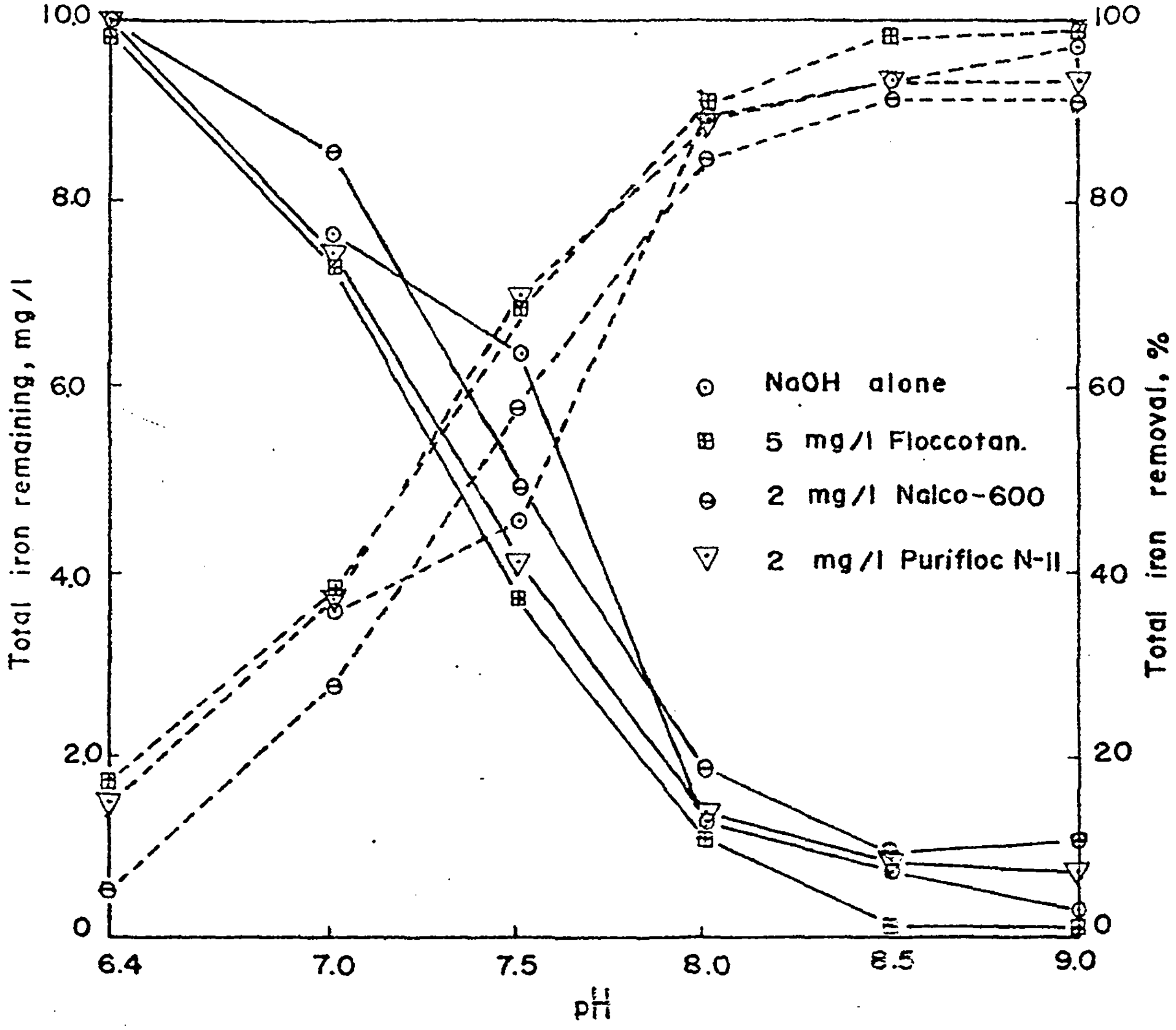


Fig. 21 — Comparison of Iron Removal at Various pH among Coagulant Aids Used with Jar Test.

Treatment with Bangkok clay The results obtained using Bangkok clay in colloidal solution are shown in Table 16 and Fig. 22. It can be seen that addition of the clay had a significant effect on iron removal. The colloidal clay sol was negatively-charged and this destabilized the positively-charged ferric oxide formed during the flash mixing of $FeSO_4 . 7H_2O$. Clay itself also acted to weight nuclei to the colloidal suspension of hydrated ferric oxide. However, it was not used as a coagulant aid in the laboratory-scale unit because of the difficulties of dosing.

Investigations Using the Laboratory - Scale Iron Removal Unit.

Table 17 shows that the rotating brushes of both units could maintain a maximum dissolved oxygen concentration of 5.2 to 5.3 mg/l in the ground water after 3-hour detention time. The dissolved oxygen level and the pH in the flocculation chamber were measured at a depth of about one fourth of the total depth of the unit. The dissolved oxygen in the flocculation basin was increased from 3.1 to 5.2 mg/l in unit no.1 and from 3.2 mg/l to 5.3 mg/l in unit no.2. The increase in dissolved oxygen content in both units was 2.1 mg/l. According to Eq. 6, 1 mg/l of dissolved oxygen can oxidize 14.7 mg/l of ferrous iron, but this amount of oxygen had only a trace effect on the removal of free CO_2 which is necessary for completion of the oxidation process as shown by Eq. 8.

The pH in both basins was raised from 6.4 to 6.5. In order to neutralize free CO_2 and raise the pH to favor iron precipitation, NaOH was used. Fig.23 and Fig. 24 show variations in dissolved

Table 16 - Chemical Analyses of Ground Water on Jar Test with Bangkok Clay as Coagulant Aid at pH 6.4

Jar No.	Turbidity	$FeSO_4.7H_2O$ added mg/l	Floc formation	After 2-hour Settling Time		
				Supernatant turbidity	Total Iron mg/l	
					Residual	% Removal
1	none	50.0	none and turbid	100	12.0	-
2	25	50.0	poor	55	2.25	80.5
3	50	50.0	poor	55	1.30	89.0
4	75	50.0	fair	55	0.90	92.5
5	100	50.0	fair	50	1.10	91.0
6	150	50.0	fair	35	0.80	93.0
7	none	25.0	none and turbid	90	6.98	-
8	25	25.0	fair	clear (25)	1.00	86.0
9	50	25.0	fair	clear	0.82	88.4
10	75	25.0	fair	clear	0.82	88.4
11	100	25.0	fair	clear	0.46	94.0
12	150	25.0	fair	clear	0.52	92.5

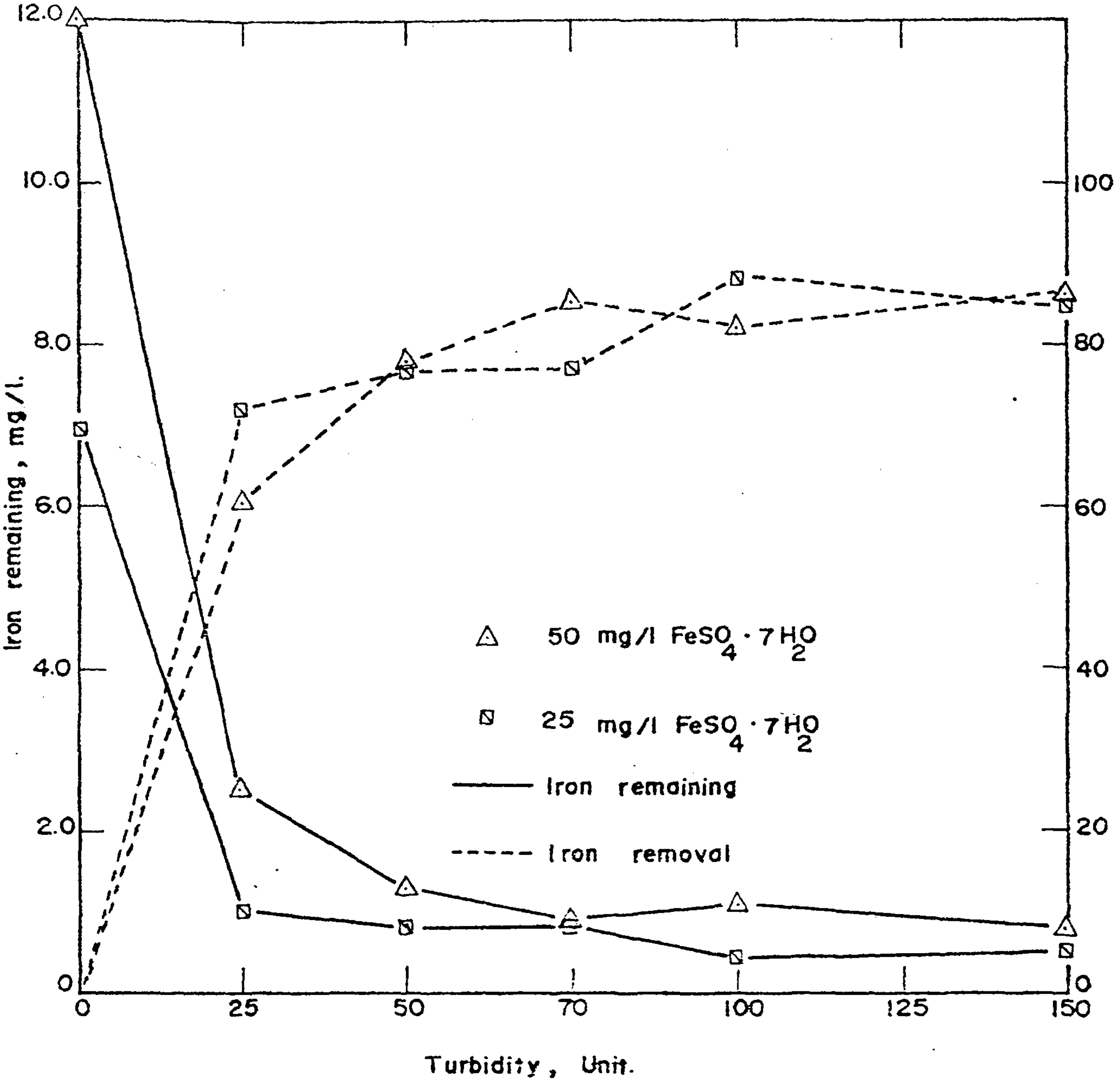


Fig.22- Iron Removal on Jar Test - with Bangkok Clay.

Table 17 - Variations in Dissolved, Oxygen, Temperature and pH During Detention Time of Three Hours

Unit no.	Dissolved Oxygen mg/1		Temperature °C		pH	
	Flocculation basin	Sedimentation basin	Flocculation basin	Sedimentation basin	Flocculation basin	Sedimentation basin
1	3.1	2.9	29.8	29.8	6.4	6.4
	3.6	2.2	29.6	29.6	6.4	6.4
	4.2	3.0	29.3	29.33	6.4	6.4
	4.5	3.1	29.3	29.1	6.4	6.4
	4.8	3.2	29.2	28.9	6.45	6.4
	5.0	3.2	29.0	28.8	6.45	6.4
	5.2	3.2	28.9	28.8	6.5	6.4
2	3.2	2.9	29.8	29.8	6.4	6.4
	3.8	2.9	29.6	29.7	6.4	6.4
	4.5	3.0	29.4	29.3	6.4	6.4
	4.7	3.1	29.3	29.1	6.4	6.4
	5.0	3.2	29.2	29.0	6.45	6.4
	5.1	3.2	28.9	28.9	6.45	6.4
	5.3	3.2	28.9	28.8	6.5	6.4

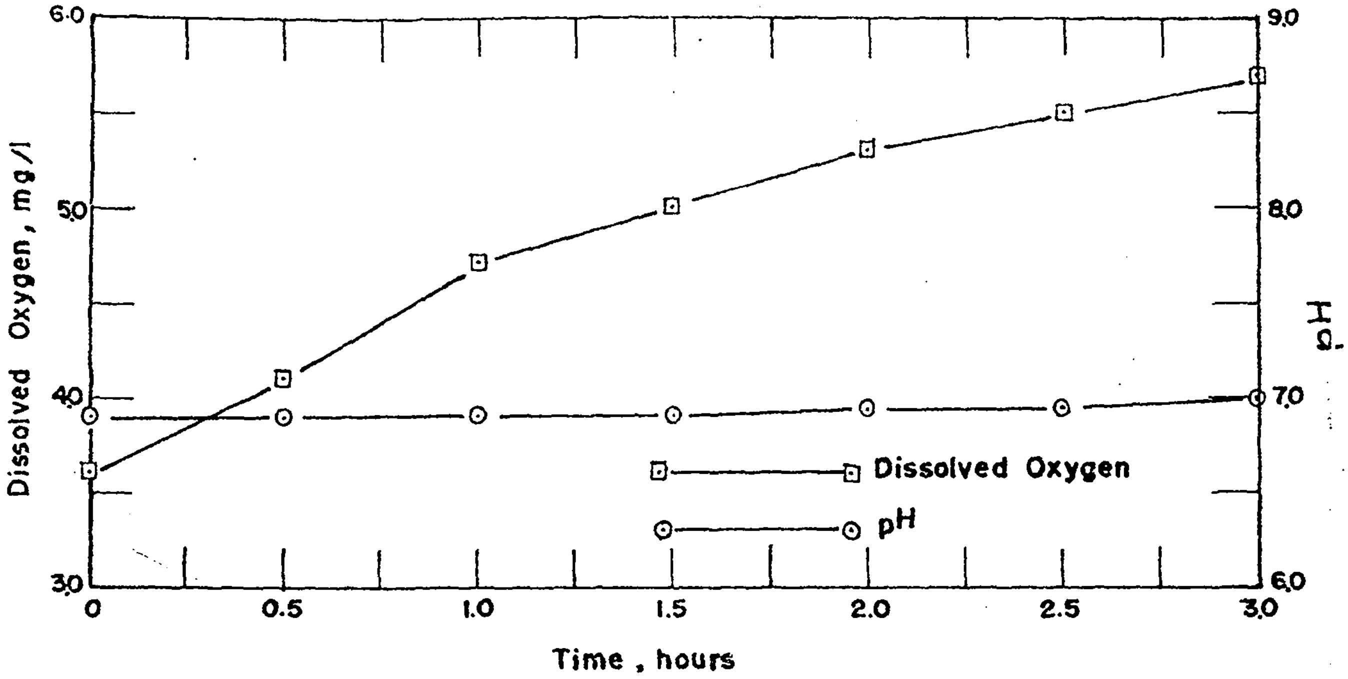


Fig. 23– Variation in Dissolved Oxygen and pH during 3–hour Detention Time in Unit no.1

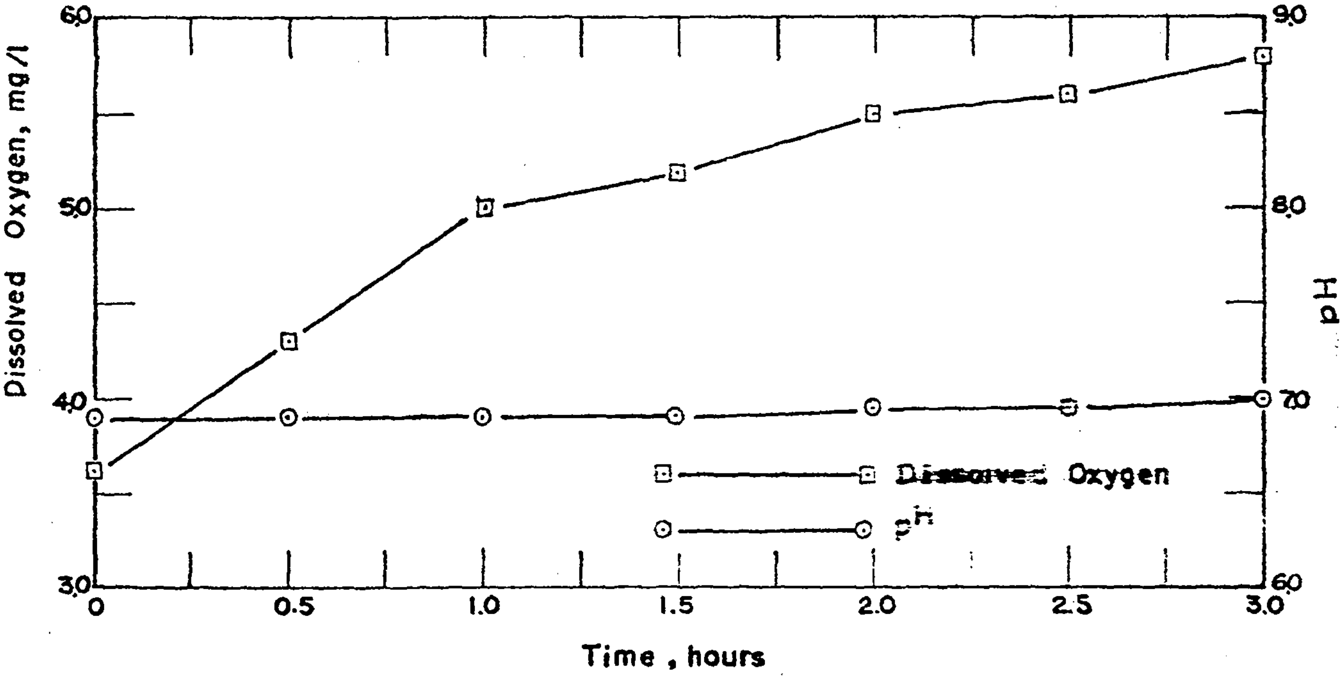


Fig. 24– Variation in Dissolved Oxygen and pH during 3–hour Detention Time in Unit no. 2

oxygen and pH during 3-hour dentention time in units 1 and 2 respectively. The rotating brushes in both units were found to have the same efficiency in providing oxygen to the ground water.

Investigations were carried out with the laboratory-scale iron removal unit in four runs. The total flow rate of ground water, NaOH, and polyelectrolyte used in each run was controlled at 54 ml/min. This was equivalent to a 3-hour total detention time in the unit, one hour in the flocculation basin and two hours in the sedimentation basin. In each test, the unit was fed with high iron-bearing ground water, with 50 mg/l $FeSO_4.7H_2O$ added, for about 27 hours to develop the insoluble iron precipitate sludge blanket at the bottom opening between the compartments. This sludge blanket tends to work both as a catalytic surface and filtering medium to the coagulated water from the flocculation basin. The depth of iron deposit measured after 27 hours, was about 4.0 cm in the sedimentation basin and about 3.0 in the flocculation basin as shown on Fig.25. The laboratory-scale unit was then fed with ground water dosed with only 25 mg/l $FeSO_4.7H_2O$ and continuously operated until the effluent showed a relatively constant concentration of iron. This took a total of about 50 hours. Analyses of the influent and effluent were carried out every two hours. After a 2-hour interval, the total quantity of 6.48 liters of influent (54 ml/min. x 60 min. x 2 hours) was assumed to have replaced the water previously occupying the sedimentation basin.

It was observed that the upflow of flocculated water from the flocculation basin did not distribute itself evenly across the bottom opening. The uneven flow did not keep all the iron precipitate suspension in the sedimentation basin. Instead, weak points formed where flocs were loosly compacted and this caused a channel flow path to form as shown in Fig. 25 and 26. This resulted in a higher upflow rate and encouraged a large number of flocs to be carried over the overflow weir. Floc formation was markedly improved when anionic or nonionic polyelectrolyte was used and the carry-over of floc was slightly reduced.

Variations of dissolved oxygen, temperature, and pH in both folcculation basin and sedimentation basin of the unit during operation in all four runs were within the same range. Maximum dissolved oxygen in the flocculation basin was in the range 5.4 mg/1 to 6.4 mg/1, pH in the range 8.4 to 8.9, and temperature in the range 25°C to 27.8°C. The difference between dissolved oxygen concentration in the influent and in the sedimentation basin indicated that oxidation of ferrous iron to ferric iron had taken place. Aeration of the influent was carried out during dosing, through the inlet tube, and by the agitation of the rotating brush.

The mechanisms of iron removal in the laboratory-scale iron removal unit were the same as those discussed in the preliminary investigations with jar tests. The ferrous iron was first oxidized to hydrated ferric oxide as shown in Eq. 27 and 28. A pH above 8.5 favored the removal of calcium alkaline and calcium non-alkaline hardness as shown in Eq. 31 and 32. Neutralization of free CO_2 in

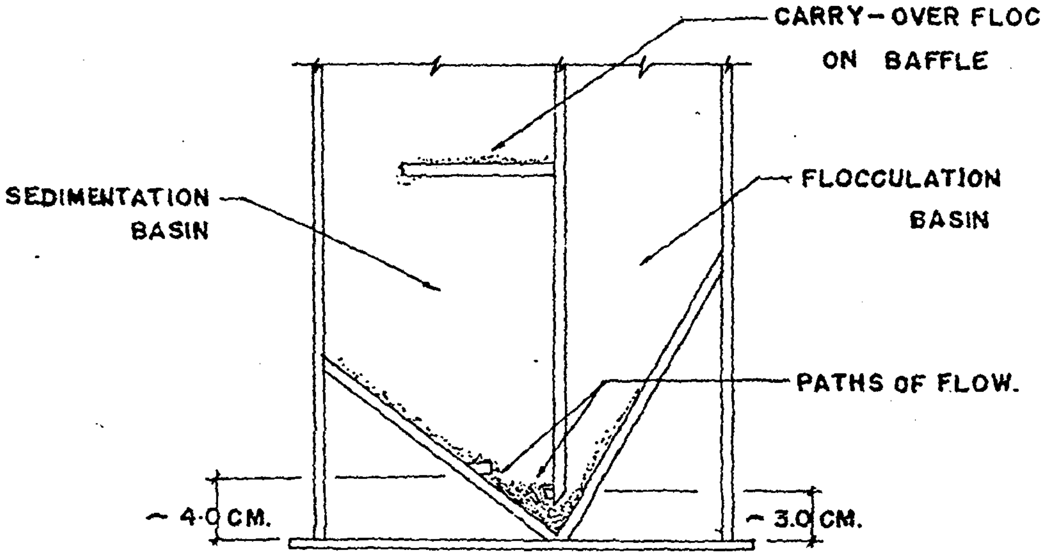


FIG. 25 – SKETCH OF FLOC DEPOSIT AFTER 27 HOURS OF OPERATION.

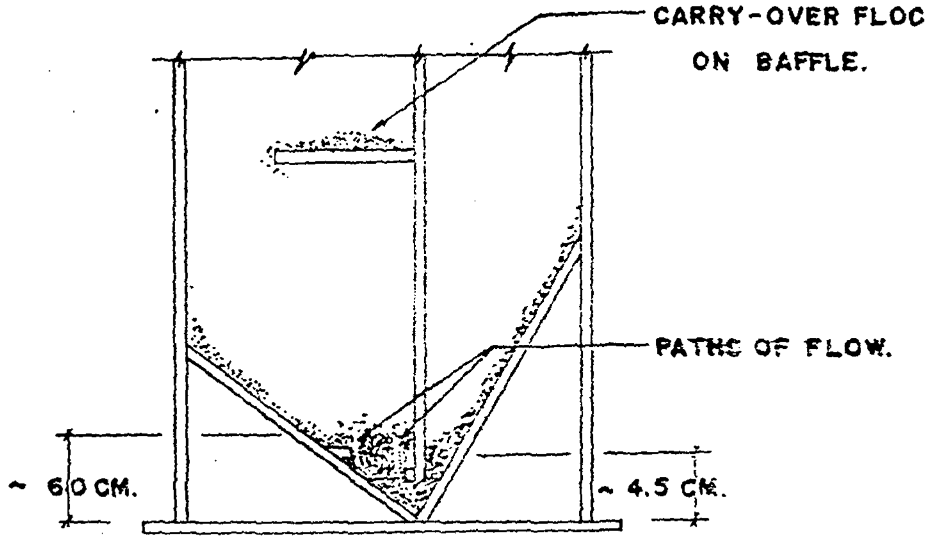


FIG. 26 – SKETCH OF FLOC DEPOSIT AFTER 50 HOURS OF OPERATION.

the influent with NaOH resulted in an effluent with high HCO_3^- alkalinity. The precipitate accumulating at the bottom of the unit probably consisted of $Fe_2O_3.xH_2O$ or $Fe(OH)_3$, hydrated ferric oxide complexes $\left[Fe_m(OH)_{n-1}\ (SO_4)_4\right]^{x-1}$, and precipitated $CaCO_3$.

<u>Treatment with NaOH</u>. The characteristics of the raw water and the conditions of the test were as follows :

1. Ground Water Characteristics:

Constituents	Original	50 mg/l $FeSO_4.7H_2O$ added	25 mg/l $FeSO_4.7H_2O$ added
pH	6.6	6.4	6.4
Hardness, mg/l $CaCO_3$	632.0	640.0	140.0
HCO_3^- alk., mg/l $CaCO_3$	308.0	282.0	297.0
Total Fe, mg/l	2.65	11.9	6.98
Fe^{++}, mg/l	2.23	8.3	5.8
Free CO_2, mg/l	78.0	92.0	90.0
Dissolved Oxygen, mg/l	3.8	1.6	0
Temperature, °C	34.0	30.0	26.0

2. Dosages :

0.1 N NaOH 2.2 ± 0.2 ml/min. = 169 ± 4.4 mg/l

Ground water 50.0 ± 2.0 ml/min.

Total 52.2 ± 2.2 ml/min.

3. Velocity of rotating brush 70 rpm.

Table 18 shows the characteristics of the ground water before and after treatment without coagulant aid and the variations in dissolved oxygen, temperature, and pH which occurred during run no.1.

TABLE 18– Ground Water Characteristics Before and After Treatment Without Coagulant Aid and Variations in D. O., Temperature, and pH in Unit no. 1 During Run no. 1

Hr	Dissolved Oxygen mg./l.		Temperature °C		pH		Chemical Analyses of Untreated and Treated Ground Water															
							pH		Alkalinity as mg/l CaCO$_3$				Dissolved Oxygen mg/l		Total Hardness as mg./l. CaCO$_3$			Fe.++ mg./l.		Total Fe mg./l.		
									HCO$_3^-$		CO$_3^=$											
	Floc. basin	Sed basin	Floc. basin	Sed basin	Floc. basin	Sed basin	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	%Rem	Inf.	Eff.	Inf.	Eff.	%Rem.
0 ⊕	4.3	4.3	29.9	29.9	8.5	7.2	6.4	7.2	282	–	–	–	1.6	–	640	–	–	8.30	–	11.80	–	–
3	6.1	5.2	27.8	28.1	8.5	7.9	6.4	7.9	282	314	–	–	–	6.1	640	491	21.7	7.48	0.01	10.95	2.48	77.4
6	6.2	5.3	27.2	27.2	8.4	8.2	6.4	8.2	284	320	–	–	–	6.2	640	482	24.7	6.94	–	10.82	2.50	77.0
9	6.4	5.4	26.1	26.1	8.5	8.2	6.4	8.2	286	338	–	–	1.8	6.5	640	481	24.8	6.12	–	10.14	1.84	73.8
22	6.3	5.1	27.2	26.8	8.6	8.45	6.45	8.4	298	341	–	18.0	–	6.9	640	468	26.9	5.28	–	8.41	1.43	83.0
27	6.4	5.2	26.6	26.4	8.6	8.3	6.45	8.3	298	348	–	–	2.7	7.1	640	452	29.4	2.80	–	7.92	0.94	88.3
31 +	5.6	5.2	25.3	25.3	8.6	8.2	6.4	8.2	297	335	–	–	0	6.5	640	456	28.7	5.80	–	6.98	0.83	88.2
43	6.1	5.4	26.3	26.3	8.5	8.1	6.4	8.1	300	312	–	–	–	6.4	6.40	478	25.3	4.84	–	6.18	0.68	89.0
49	6.2	5.5	25.3	25.3	8.6	8.2	6.5	8.2	302	346	–	–	–	6.5	640	480	25.0	2.34	–	4.35	0.48	89.0
51	6.3	5.5	25.2	25.1	8.5	8.2	6.5	8.2	306	342	–	–	0.8	6.5	640	460	28.1	2.01	–	4.02	0.61	85.0
52 +	6.1	5.4	25.8	25.8	8.5	8.2	6.5	8.2	314	335	–	–	0	6.5	640	476	25.6	5.14	–	7.02	0.78	89.0
54	6.2	5.6	26.6	26.3	8.4	8.2	6.5	8.2	314	338	–	–	–	6.4	640	478	25.3	4.98	–	6.94	0.64	90.8
56	6.2	5.7	26.4	26.3	8.5	8.1	6.5	8.1	314	325	–	–	–	6.5	640	482	24.7	4.53	–	6.34	0.58	91.0
58	6.2	5.7	26.4	26.4	8.5	8.2	6.5	8.2	316	330	–	–	–	6.5	640	496	25.6	3.94	–	5.84	0.60	89.4
60	6.3	5.7	26.2	26.1	8.6	8.2	6.5	8.2	318	332	–	–	–	6.5	640	484	24.4	3.81	–	5.62	0.61	86.0
62	6.3	5.7	26.0	26.0	8.5	8.3	6.5	8.3	318	338	–	–	0	6.5	640	482	24.7	3.04	–	5.28	0.80	88.7

⊕ Start feeding with 50 mg./l. FeSO$_4$·7H$_2$O as supplement to influent.

\+ Start feeding with 25 mg./l. FeSO$_4$·7H$_2$O as supplement to influent.

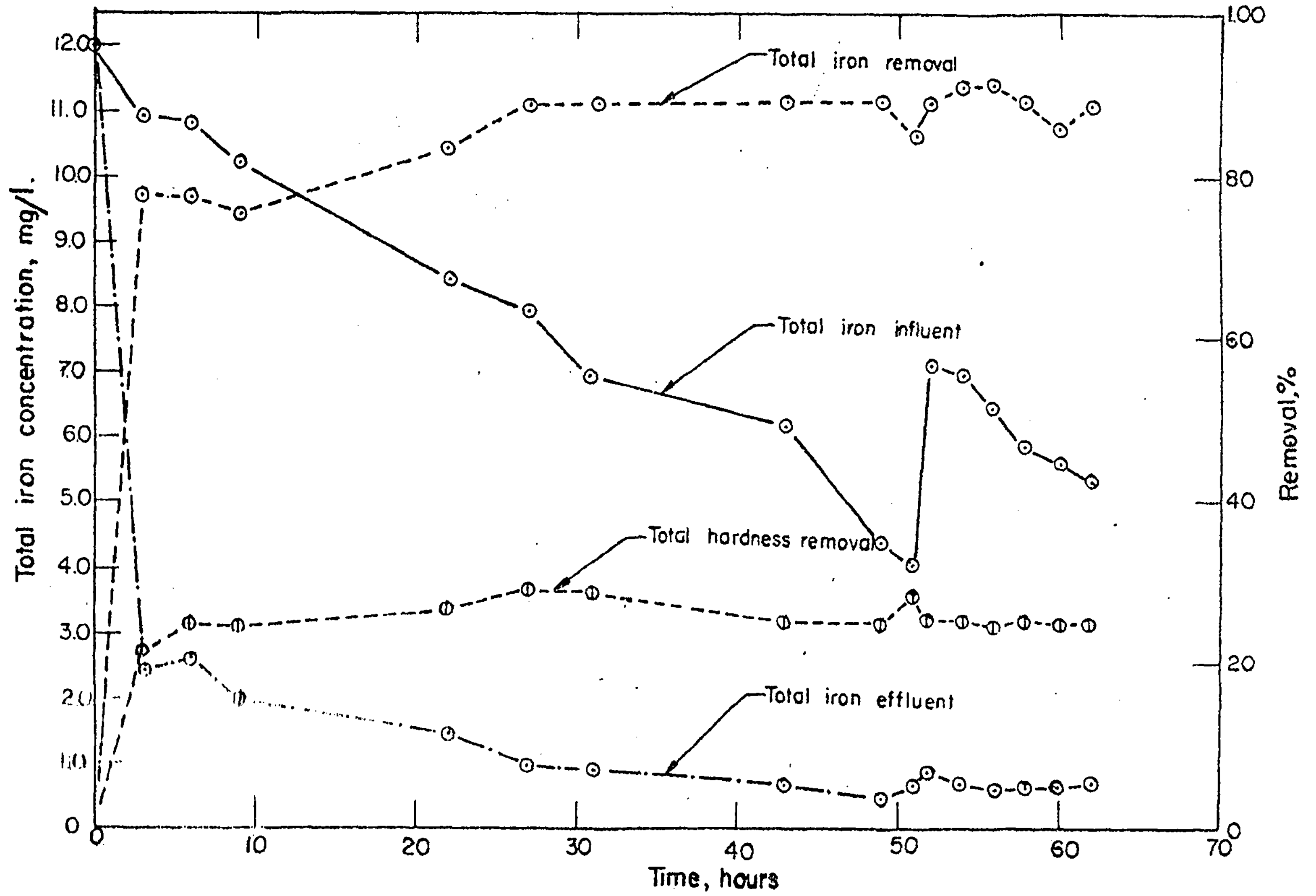


Fig. 27 – Total Iron and Hardness Removal without Coagulant Aid during Run no. 1.

Total iron removal was in the range from 85 to 90% and total hardness removal was from 25 to 28%. The pH in the sedimentation section varied between 8.4 to 8.6 with a dose of 0.1 N.NaOH of 2.2 ± 8.2 ml/min. or 42.5 ± 0.9 ml per liter of total flow rate. This was equivalent to an NaOH dose of 169 ± 4.4 mg/l.

Comparison of the results obtained in the jar test (Table 6) with those in the laboratory-scale unit (Table 18) shows that in the same pH range from 8.4 to 8.6, the percentage of total iron removal in the laboratory-scale unit was lower than the percentage of iron removal in the jar test. The percentage of total hardness removal in the laboratory-scale unit was higher than in the jar test. This indicated unsuccessful operation of the ferric oxide blanket as a filtering medium. It was observed that the upflow path through the sludge blanket caused light, slimy, gelatinous .ydrated ferric oxide precipitate to be carried over to the effluent overflow wier while the heavier $CaCO_3$ precipitates were not moved. Polyelectrolyte was then used in an attempt to avoid this type of failure.

Analyses of the treated water from treatment with sodium hydroxide showed only a trace or zero ferrous iron. This was because the ferrous iron could be readily oxidized in the presence of high OH^- ion concentration at high pH. Fig.27 illustrates the variations which occurred in total iron and total hardness removal in the laboratory-scale unit during run no.1. The pH in the flocculation basin was kept in the range 8.4 to 8.6. The percentage of iron removal was low at the beginning of the 3rd hour at 77.4% and, gradually increased to 88.3 % at the 27th hour of operation, and thereafter tended to be more consistent in the range 82 to 91 %. At the beginning of operation, the previously-accumulated precipitated iron blanket was not sufficient to act as a filtering medium and catalytic surface to the flocculated water from the flocculation basin. The percentage of iron removal was not highly improved after 27 hours of operation and it was observed that there were tiny suspended gelatinous iron flocs above the precipitated iron blanket rerulting from channel-path flow. Total hardness removal was dependent upon the pH in the unit as indicated in the preliminary investigations using jar tests. Because of the slight variation of pH in the flocculation basin from 8.4 to 8.6, the total hardness removal was found to be in the range 22 to 29%.

Treatment with coagulant aid. The characteristics of the raw water and the conditions of the test when the anionic polyelectrolyte FLOCCOTAN was used were as follows:

1. Ground water characteristics :

Constituents	Original	50 mg/l $FeSO_4.7H_2O$ added	25 mg/l $FeSO_4.7H_2O$ added
pH	6.6	6.4	6.5
Hardness, mg/l $CaCO_3$	632.0	640.0	640.0
HCO_3^- alk., mg/l $CaCO_3$	308.0	285.0	268.0
Total Fe, mg/l	2.65	12.1	7.40
Fe^{++}, mg/l	2.32	7.94	4.94
Free CO_2, mg/l	78.0	94.0	82.0
Dissolved Oxygen, mg/l	3.8	1.8	0
Temperature, °C	34.0	30.0	26.0

2. Dosages

0.1N.NaOH	2.2 ± 0.2	ml/min. or 169 ± 4.4 mg/l
FLOCCOTAN	2.7 ± 0.2	ml/min. or 5 mg/l
Ground Water	47.0 ± 2.0	ml/min.
Total	51.9 ± 2.4	ml/min.

3. Velocity of rotating brush 70 rpm.

The FLOCCOTAN was used at concentration of 5 mg/l in conjunction with NaOH to keep pH in the same range as before (pH 8.4 to 8.6). Iron removal was slightly improved as shown in Table 19. The precipitates formed were highly improved in toughness, weight and size and slimy and gelatinous iron precipitates no longer existed. The negative charges on polymeric molecules of the FLOCCOTAN facilitated flocculation of positively charged ferric hydroxo complexes and polymers. Floc carry-over to the effluent overflow weir was reduced. There was no indication of any effect on total hardness removal when FLOCCOTAN was used. The results presented in Fig.28 show the variations of total iron removal and total hardness during run no.2. The percentage of iron removal was markedly improved compared with 79.2% at the 3rd hour and 92.7% at the 52nd hour of operation. The tough and dense flocs formed diminished the floc carry-over problem, but still short circuiting through the precipitated iron blanket lowered the efficiency of iron removal in this type of unit. Total hardness removal showed little variation from 24.6 to 26.5%.

The characteristics of the raw water and the condition of the test when the cationic polyelectrolyte Nalco-600 was used as follows:

TABLE 19– Ground Water Characteristics Before and After Treatment with 5 mg./l. Floccotan as Coagulant Aid and Variations in D.O., Temperature and pH. in Unit no. 2, During Run no. 2,

Hr	Dissolved Oxygen mg./l.		Temperature °C		pH		Chemical Analyses of Untreated and treated Ground Water.															
							pH		Alkalinity as mg/l. $CaCO_3$				Dissolved Oxygen mg./l.		Hardness as mg./l. $CaCO_3$			Fe mg./l.		Total Fe mg./l.		
	Floc. basin	Sed. basin	Floc. basin	Sed. basin	Floc. basin	Sed. basin			HCO_3^-		$CO_3^=$											
							Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	%Rem.	Inf.	Eff.	Inf.	Eff.	%Rem.
0	4.3	4.2	30.0	30.0	8.4	7.1	6.4	7.1	285	–	–	–	1.8	–	640	–	–	7.94	–	12.10	–	–
3	6.2	5.2	27.8	28.0	8.5	8.0	6.4	8.2	285	334	–	–	–	5.9	640	540	15.6	7.21	0.02	11.52	238	79.2
6	6.2	5.3	27.2	27.2	8.5	8.2	6.4	8.2	286	341	–	–	–	6.2	640	482	24.7	6.01	–	9.84	2.03	79.5
9	6.4	5.3	26.0	26.0	8.6	8.3	6.4	8.3	288	366	–	–	2.1	6.2	640	468	26.8	4.82	–	9.92	1.83	71.4
22	6.3	5.2	27.0	26.5	8.6	8.4	6.5	8.4	296	364	–	12.0	–	6.6	640	476	25.6	1.74	–	7.82	1.18	84.3
27	6.4	5.4	26.4	26.4	8.5	8.3	6.5	8.3	296	332	–	–	3.2	6.8	640	478	25.3	1.34	–	7.60	1.21	84.0
31	5.7	5.1	25.0	25.0	8.5	8.2	6.5	8.2	288	336	–	–	0	6.5	640	482	24.7	4.94	–	7.40	0.85	88.7
43	6.0	5.4	26.2	26.2	8.4	8.7	6.5	8.4	292	332	–	24.0	–	6.4	640	470	26.5	4.31	–	6.70	0.58	91.4
49	6.1	5.4	25.9	25.9	8.6	8.3	6.5	8.3	296	348	–	–	–	6.5	6.40	474	26.0	2.80	–	4.15	0.51	87.8
51	6.0	5.4	25.8	25.8	8.6	8.3	6.5	8.3	300	348	–	–	0.8	6.5	640	478	25.3	2.41	–	3.98	0.48	88.0
52	6.0	5.5	26.2	26.0	8.6	8.3	6.5	8.3	308	352	–	–	0	6.4	640	481	24.8	4.28	–	7.18	0.53	92.7
54	6.0	5.5	26.7	26.3	[illegible]	8.3	6.5	8.3	308	350	–	–	–	6.5	640	483	24.6	4.61	–	6.84	0.49	92.9
56	6.2	5.6	26.6	26.3	8.5	8.2	6.5	8.2	310	336	–	–	–	6.5	640	480	25.0	4.58	–	6.04	0.46	92.5
58	6.2	5.7	26.4	26.3	8.6	8.2	6.6	8.2	314	330	–	–	–	6.5	640	482	24.7	4.23	–	5.92	0.47	92.0
60	6.2	5.8	26.3	26.3	8.6	8.2	6.5	8.2	314	332	–	–	–	6.5	640	480	25.0	3.94	–	5.84	0.47	92.0
62	6.3	5.8	25.8	25.8	8.6	8.3	6.5	8.3	314	348	–	–	0.5	6.5	640	472	26.2	3.68	–	5.71	0.46	91.8

Start feeding with 50 mg./l. $FeSO_4 \cdot 7H_2O$ as Supplement to influent.

Start feeding with 25 mg./l. $FeSO \cdot 7H_2O$ as Supplement to influent

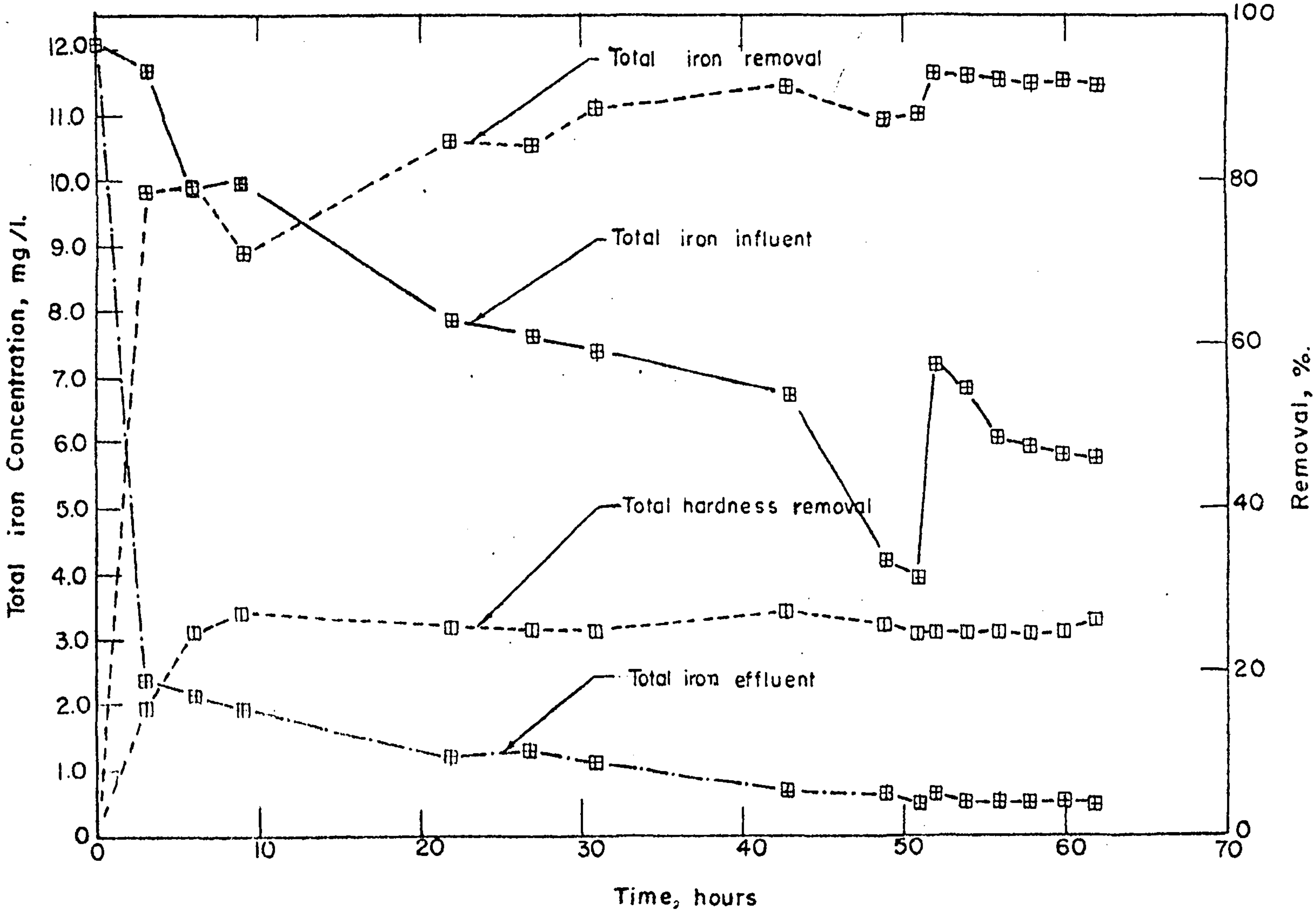


Fig. 28 — Total Iron and Hardness Removal with 5 mg/l. Floccotan as Coagulant Aid during Run no. 2.

1. Ground water characteristics.

Constituents	Original	50 mg/l $FeSO_4 \cdot 7H_2O$ added	25 mg/l $FeSO_4 \cdot 7H_2O$ added
pH	6.6	6.5	6.5
Hardness, mg/l $CaCO_3$	556.0	556.0	556.0
HCO_3^- alk., mg/l $CaCO_3$	324.0	310.0	328.0
Total Fe, mg/l	2.56	12.85	7.75
Fe^{++}, mg/l	2.29	9.64	4.62
Free CO_2, mg/l	88.0	90.0	94.0
Dissolved Oxygen, mg/l	0.8	0	0
Temperature, °C	34.0	30.0	26.0

2. Dosages

0.1 N.NaOH 2.4 ± 0.2 ml/min. or 186 ± 4.8 mg/l

Nalco-600 1.2 ± 0.2 ml/min. or 2 mg/l

Ground water 48.0 ± 2.0 ml/min.

Total 51.6 ± 2.4 ml/min.

3. Velocity of rotating brush 70 rpm.

Table 20 shows the ground water characteristics before and after treatment with 2 mg/l cationic Nalco-600 and the variations in dissolved oxygen, temperature, and pH which occurred during run 3. Fig.29 represents variations in total iron removal and total hardness removal during 3. Total iron removal and total hardness removal were found to be slightly improved compared with run 1. This was because of the dose of NaOH in run 3 was raised to 186 ± 4.8 mg/l

TABLE 20. Ground Water Characteristics Before and After Treatment with 2 mg/l Nalco-600 as Coagulant Aid and Variations in D.O., Temperature, and pH in Unit no. 1, During Run no. 3.

Hr.	D.O. mg/l		Temperature °C		pH		Chemical Analyses of Untreated and Treated Ground Water															
							pH		Alkalinity as mg/l CaCo3				D.O. mg/l		Total Hardness as mg/l CaCo3			Fe++ mg/l		Total Fe mg/l		
									HCO3-		CO3=											
	Floc. basin	Sed. basin	Flod. basin	Sed. basin	Floc basin	Sed basin	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	%Ren	Inf.	Eff.	Inf.	Eff	%Ren
0⊕	2.9	2.8	29.8	29.8	8.4	7.0	6.5	7.0	310	–	–	–	0	556	–	–	9.64	–	–	12.85	–	–
3	5.1	3.4	28.2	28.0	8.5	7.8	6.5	7.8	310	320	–	–	–	4.3	556	487	12.4	9.20	0.03	12.62	3.28	74.10
6	5.3	3.8	27.3	27.3	8.7	8.3	6.5	8.2	310	340	–	–	–	4.8	556	423	23.9	8.90	0.01	12.30	2.62	78.70
9	5.4	4.1	25.6	25.6	8.6	8.3	6.5	8.4	310	356	–	–	0	5.2	556	381	31.5	8.80	–	11.20	1.28	97.75
22	6.1	5.0	27.0	27.0	8.3	8.1	6.55	8.1	300	326	–	–	–	6.4	556	383	31.1	4.20	–	10.10	1.20	88.10
27	6.1	5.0	26.8	26.8	8.4	8.2	6.55	8.2	300	342	–	–	0.4	6.4	556	398	28.4	3.80	–	9.90	1.30	86.54
+31	6.2	5.1	25.4	25.4	8.6	8.3	6.5	8.4	328	360	–	–	0	6.3	556	384	31.0	4.62	–	7.75	1.11	85.50
43	6.2	5.1	26.1	26.2	8.4	8.2	6.5	8.2	328	346	–	–	–	6.3	556	389	30.0	3.32	–	6.10	1.20	80.30
49	6.3	5.2	25.9	25.9	8.5	8.2	6.5	8.2	320	340	–	–	–	6.4	556	391	29.6	2.58	–	4.40	0.98	77.80
51	6.3	5.2	25.8	25.7	8.6	8.2	6.5	8.3	320	342	–	–	0.2	6.6	556	390	30.0	2.32	–	4.80	0.60	87.50
+53	6.2	5.2	26.2	26.2	8.6	8.3	6.4	8.3	300	358	–	–	0	6.4	556	382	31.3	5.30	–	7.20	0.88	88.10
55	6.2	5.3	20.2	26.2	8.7	8.4	6.4	8.4	302	332	–	32.0	–	6.5	556	380	31.6	5.00	–	7.10	0.57	92.00
56	6.2	5.3	20.2	26.2	8.6	8.3	6.4	8.3	310	352	–	8.0	–	6.5	556	384	31.0	4.95	–	6.80	0.62	91.00
58	6.2	5.3	26.1	26.1	8.6	8.3	6.4	8.4	302	350	–	–	–	6.5	556	390	29.7	4.60	–	6.50	0.58	91.40
60	6.2	5.3	26.0	26.0	8.6	8.3	6.4	8.3	300	348	–	–	–	6.5	556	395	29.0	4.18	–	580	0.52	91.00
62	6.2	5.3	25.9	25.9	8.6	8.3	6.4	8.3	308	350	–	–	0	6.6	556	384	31.0	3.72	–	588	0.50	91.00

⊕ Start feeding with 50 mg/l $FeSo_4$ $7H_2O$ as supplement to influent.

+ Start feeding with 25 mg/l. FeSo 7H O as supplement to influent.

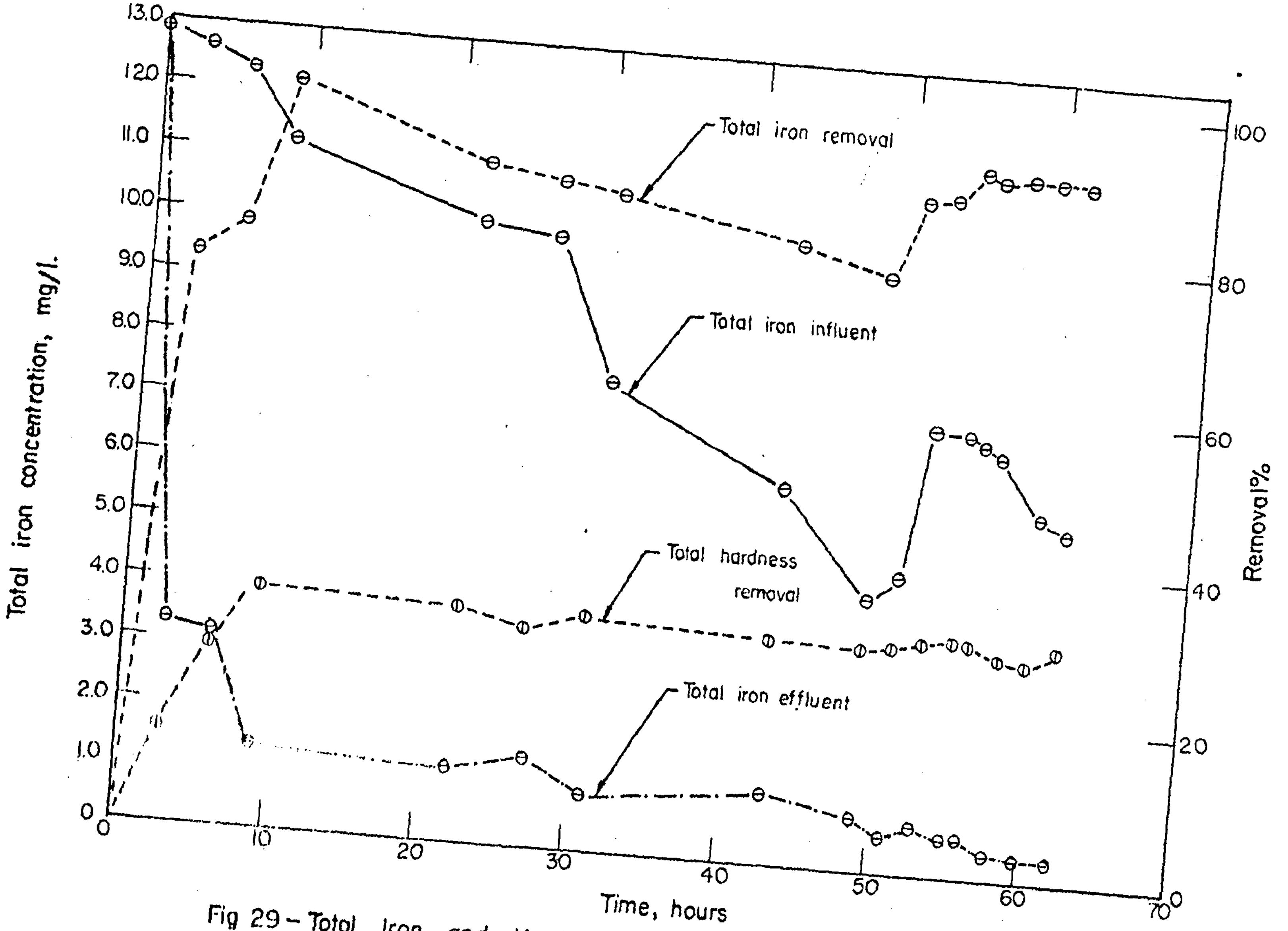


Fig 29 – Total Iron and Hardness Removal with 2 mg/l Nalco-600 as Coagulant aid during run no. 3

compared with 169 ± 4.4 mg/l of run 1. During the course of addition of cationic Nalco-600 it was that the flocs formed were relatively small and dense with a less slimy and gelatinous structure than the flocs of run 1. The cationic Nalco-600 provided positively-charged polymeric ions to neutralize the negatively-charged $CaCO_3$ precipitates and some negatively-charged ferric hydroxo polymers which might be present in the water at high pH values. The carry-over of floc was still observed, but to a lesser degree than that in run 1. From Fig. 29, the percentage of iron removal gradually increased as the precipitated iron blanket grew thicker but still the channel flow formed in the blanket, sometimes reducing the efficiency of iron removal. At the 9th hour of operation, the percentage of iron removal was as high as 97.75%. This might have been due to high pH of 8.7 at the 6th hour and pH 8.6 at the 9th hour in the flocculation basin together with high iron content in the influent of 11.20 mg/l of iron, thus favoring a high percentage of iron removal.

The characteristics of the raw water and the conditions of the test when nonionic polyelectrolyte, PURIFLOC N-11 was used, as follows:

1. Ground water characteristics

Constituents	Original	50 mg/l $FeSO_4.7H_2O$ added	25 mg/l $FeSO_4.7H_2O$ added
pH	6.6	6.4	6.4
Hardness, mg/l $CaCO_3$	556.0	556.0	556.0
HCO_3^- alk., mg/l $CaCO_3$	324.0	316.0	318.0

Total Fe, mg/l	2.56	12.60	7.80
Fe^{++}, mg/l	2.29	9.80	4.82
Free CO_2, mg/l	88.0	96.0	94.0
Dissolved Oxygen, mg/l	0.8	0	0
Temperature, °C	34.0	30.0	25.4

2. Dosages

0.1N.NaOH	2.4 ± 0.2 ml/min. or 186 ± 4.8 mg/l
PURIFLOC N-11	1.2 ± 0.2 ml/min. or 2 mg/l
Ground Water	48.0 ± 2.0 ml/min.
Total	51.6 ± 2.4 ml/min.

3. Velocity of rotating brush 70 rpm.

Table 21 shows the ground water characteristics before and after treatment with 2 mg/l nonionic PURIFLOC N-11 and the variations in dissolved oxygen, temperature, and pH which occurred during run 4. Fig.30 represents variations in total iron removal and total hardness removal during the run. Table 21 shows that when PURIFLOC N-11 at a concentration of 2 mg/l was used, carry-over flocs were found to be reduced, giving rise to a higher total iron removal. The floc was observed to be very tough and relatively smaller in size than the flocs formed with FLOCCOTAN in run 2. The nonionic PURIFLOC N-11 provided both positively- and negatively- charged polymeric ions for the high ferric hydroxo polymers and ferric hydroxo complexes, and for the negatively-charged suspended $CaCO_3$ precipitates, thus facilitating floc formation. Fig.30 shows that the percentage of total iron removal was gradually increased as the precipitated-iron

TABLE 21 – Ground Water Characteritics Before and After Treatment with 2 mg./l. PURIFLOC N-11 as Coagulant Aid and Variations in D.O., Temperature and pH in Unit no. 2, During Run no. 4.

Hr.	Dissolved Oxygen mg./l.		Temperature °C		pH		Chemical Analyses of Untreated and Treated Ground Water.															
							pH		Alkalinity as mg./l. $CaCO_3$				Dissolved Oxygen mg./l.		Hardness as mg./l. $CaCO_3$			Fe^{++} mg./l.		Total Fe		
	Floc. basin	Sed. basin	Floc. basin	Sed basin	Floc. basin	Sed basin			HCO_3^-		$CO_3^=$											
							Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	Inf.	Eff.	%Rem	Inf.	Eff.	Inf.	Eff.	%Rem.
0 ⊕	2.9	2.9	29.8	29.0	8.4	7.0	6.4	7.1	316	–	–	–	0	–	556	–	–	9.80	–	12.60	–	–
3	5.2	3.5	28.9	28.7	8.4	7.8	6.4	7.8	314	318	–	–	–	4.2	556	4.84	12.9	9.20	0.06	12.30	3.80	69.70
6	5.3	3.8	27.5	27.5	8.4	8.0	6.4	7.9	314	328	–	–	–	4.8	556	418	24.8	8.70	0.03	12.00	2.68	77.75
9	5.5	3.9	25.8	25.8	8.6	8.4	6.45	8.4	310	318	–	32.0	–	5.1	556	396	28.7	7.20	–	11.50	2.52	78.00
22	6.3	5.1	27.0	26.9	8.5	8.3	6.5	8.3	300	336	–	–	–	6.3	556	382	31.3	3.80	–	10.18	1.80	82.40
27	6.3	5.1	26.3	26.3	8.4	8.3	6.5	8.3	310	342	–	–	0.5	6.4	556	398	28.4	3.10	–	10.20	1.82	82.30
31 +	6.2	5.2	25.4	25.5	8.4	8.3	6.4	8.3	318	346	–	–	0	6.6	556	384	31.0	4.82	–	7.80	1.02	88.20
43	6.3	5.2	26.2	26.2	8.9	8.5	6.5	8.5	318	292	–	72.0	0	6.4	556	378	32.0	4.10	–	7.20	0.52	92.80
49	6.4	5.3	25.9	25.9	8.8	8.4	6.5	8.4	318	350	–	12.0	0.8	6.7	556	382	31.3	3.00	–	5.25	0.62	88.25
51	6.3	5.3	25.9	25.7	8.5	8.2	6.5	8.2	316	344	–	–	–	6.8	556	380	31.7	2.90	–	5.00	0.58	88.40
53 +	6.3	5.3	26.2	26.2	8.8	8.5	6.5	8.3	298	338	–	–	0	6.8	556	382	31.3	5.20	–	7.20	0.70	90.40
55	6.3	5.3	26.2	26.2	8.7	8.4	6.5	8.4	300	338	–	–	–	6.4	556	370	33.4	4.89	–	7.08	0.64	91.00
57	6.4	5.3	26.2	26.2	8.6	8.3	6.5	8.3	302	338	–	12.0	–	6.4	556	377	32.1	4.60	–	6.80	0.32	95.30
59	6.4	5.3	26.1	26.1	8.8	8.4	6.5	8.4	306	346	–	8.0	–	6.4	556	384	32.3	4.40	–	6.54	0.34	95.00
61	6.4	5.3	26.0	25.0	8.4	8.2	6.5	8.2	310	324	–	–	–	6.4	556	387	30.4	4.30	–	6.04	0.34	94.50
63	6.4	5.3	25.9	25.9	8.5	8.2	6.5	8.2	310	326	–	–	–	6.5	556	380	31.6	4.00	–	5.98	0.32	95.00

⊕ Start feeding with 50 mg./l. $FeSO_4 \cdot 7H_2O$ as supplement to influent

\+ Start feeding with 25 mg./l. $FeSO_4 \cdot 7H_2O$ as supplement to influent.

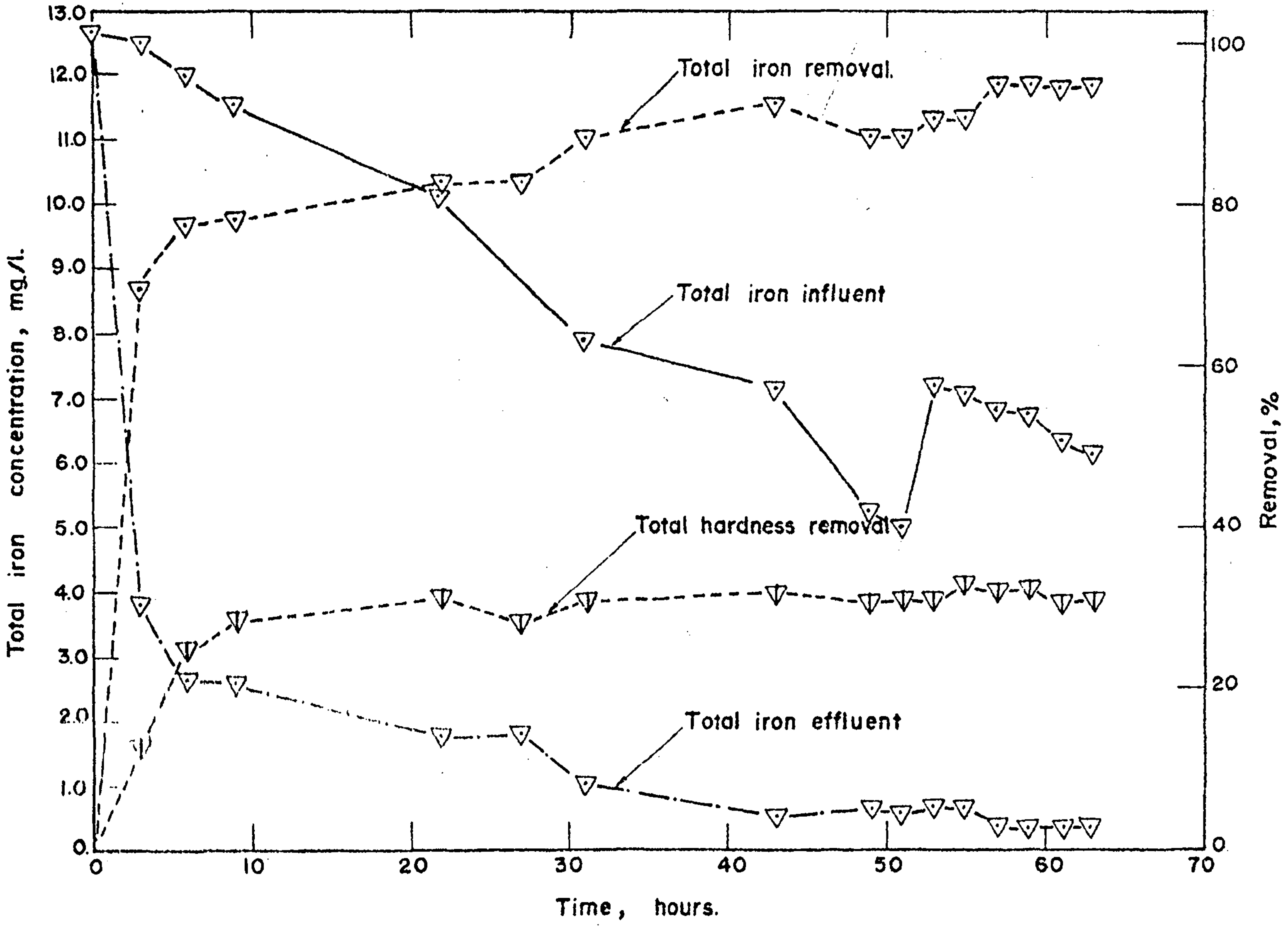


Fig. 30— Total Iron and Hardness Removal with 2 mg./l. Purifloc N-II as Coagulant Aid during Run no. 4.

blanket increased in thickness and tended to be constant at the 57th hour of operation. Because of the higher dose of NaOH, total hardness removal was generally higher than that obtained in runs 1 and 2.

From the results of the experimental investigations carried out in the laboratory-scale unit, it was found that the quality of the finished water in all four runs wasup to neither the USPHS (1962) Drinking Water Standards nor the W.H.O. (1963) International Drinking Water Standards. The iron concentration in the treated water generally above the recommended 0.3 mg/l. It was observed that the iron content in the finished water was in the form of tiny insoluble particles of precipitated iron. These could be readily settled out under gravity if left for a short period.

Because of the rather high concentration of total hardness in the ground water used in the experiments, the total hardness of the finished water was generally greater than 300 mg/l as $CaCO_3$. The bicarbonate alkalinity of the treatment water was found to increase, probably due to neutralization of free CO_2 present in the influent with the NaOH added. The pH of the treated water was found to be as high as 8.5 in run 3, which is just within the 7.0 to 8.5 pH range recommended in the W.H.O. (1963) International Drinking Water Standards.

VI - CONCLUSIONS

The following conclusions may be drawn from the study :

1. Iron concentration in the ground water was found to vary a great deal from well to well. The average iron concentration in the ground water of Thailand according to the availabel data was found to be in excess of both the 1962 USPHS recommended limits and the W.H.O. (1963) permissible level of 0.3 mg/l. High iron-bearing ground water is commonly found in the northeastern part of Thailand whereas in the central part of the country, deep wells generally produce ground water of more acceptable quality, with relatively low iron content.

2. The results obtained from jar test indicated that when NaOH was used for pH adjustment, most efficient iron removal was obtained when the pH value was between 8.5 and 9.0.

Of the three types of polyelectrolytes used as coagulant aids in the jar tests, 5 mg/l of FLOCCOTAN at the optimum pH values of 8.5 to 9.0 was found to be most effective from the standpoint of floc formation and iron removal. Polyelectrolytes of the anionic type and nonionic type were found to stimulate agglomeration of precipitated iron into larger and heavier flocs compared with iron precipitates formed with pH adjustment alone or with addition of cationic polyelectrolytes. Use of polyelectrolyte as coagulant aid was not found to have any effect on total hardness removal.

3. The laboratory-scale iron removal unit, with design based on upflow solids-contact clarification having three hours detention time,

was not found to give satisfactory iron removal. Upflow through the bottom opening was not very well distributed and did not keep accumulated insoluble ferric precipitates in suspension. A channel flow path with relatively high velocity was created by the existance of loosely compacted flocs. A high percentage of lighter flocs was thus carried over the effluent weir.

Insoluble iron floc was effectively formed when the pH in the flocculation basin was kept within the values of 8.5 and 9.0. Addition of 2 mg/l cationic polyelectrolyte, Nalco - 600, at a pH between 8.5 and 9.0, was found to give a slight improvement in floc formation. However, when 5 mg/l FLOCCOTAN or 2 mg/l nonionic PURIFLOC N-11 was used, floc formation was markedly better. This resulted in an increase in the removal of iron. Further improvement might be obtained if the laboratory - scale iron removal unit was modified to keep the sludge blanket in suspension or if the depth of the unit was increased. Unfortunately, limited time prevented modifications being made.

4. During the course of these investigations, it was found difficult to prevent ferrous iron in the influent from being oxidized to ferric iron in the influent reservoir prior to treatment.

VII RECOMMENDATIONS FOR FUTURE WORK

The present project was a study of iron removal by the laboratory-scale unit designed on the basis of the upflow solids-contact clarification process. This work might be regarded as preliminary development of a low-cost iron removal unit for rural areas.

Some suggestions for further work which might be carried out in the future are as follows:

1. Further study of upflow velocity to keep the iron sludge blanket in continuous suspension and the length of upflow that will diminish the carry-over of floc to the effluent overflow weir.

2. A study of the effect of other chemical coagulants such as lime, soda ash, etc., with various aeration processes on iron removal. Another study should be carried out using clay as coagulant aid in the pilot plant designed.

3. A study of the factors that govern the kinetics of iron precipitation of some typically high iron-bearing ground waters in the northeastern part of Thailand so that a more rational approach can be applied to the design of an iron removal plant on a practical scale.

4. Investigations into the effect of iron bacteria on iron precipitation in the upflow solids-contact clarification process.

REFERENCES

AMERICAN PUBLIC HEALTH ASSOCIATION, AMERICAN WATER WORKS ASSOCIATION, and WATER POLLUTION CONTROL FEDERATION (1965), Standard Methods for the Examination of Water and Wastewater, 12th ed., Am.Publ. Hlth Ass., Inc., New York.

AMERICAN WATER WORKS ASSOCIATION (1951), Water Quality and Treatment, The Am. Wat. Wks. Ass., Inc., New York.

AMERICAN WATER WORKS ASSOCIATION COMMITTEE (1951), Capacity and Loadings of Suspended Solids Contact Units, J. Am. Wat. Wks Ass., v. 54, pp. 263-291.

BOND, A.W. (1961) Upflow Solids Contact Basin, J.San.Engng Div., Proc., Am. Soc. civ. Engrs, v. 87, SA 6, pp. 73-99.

BABCOCK, R.H. (1950), Iron and Manganese Removal by Spaulding Precipitator, J. of the New Engl. Wat. Wks Ass., v. 64, no.2, pp. 138-47.

BENSON, B.E. (1965), Treatment for High Iron Content in Remote Alaskan Water Supplies, Arctic Health Research Centre, Anchorage.

BABBITT, H.E., DOLAND, J.J., and CLEASBY, J.L. (1959), Water Supply Engineering, McGraw-Hill Book Company, Inc., New York.

CONNELLEY, E.J. (1958), Removal of Iron and Manganese, J. Am. Wat. Wks Ass., v. 50, pp. 697-708.

COHEN, J.M., ROURKE, G.A., and WOODWARD, R.L.(1958), Natural and Synthetic Polyelectrolytes as Coagulant Aids. J.Am.Wat.Wks Ass., v. 50, pp. 463-478.

FAIR, G.M. and GEYER, I.C. (1954), *Water Supplies and Waste-Water Disposal*, John Wiley & Sons, Inc., New York.

GHOSH, M.M., O'CONNOR, J.T., and ENGELBRECHT, R.S. (1966), Precipitation of Iron in Aerated Ground Waters, *J.San. Engng Div., Proc. Am. Soc. civ. Engrs*, v. 92, SA 1, pp. 199-213.

GHOSH, M.M. (1965), *Filtration as Related to the Removal of Iron from Ground Waters*, Dep. of Civil Engng, Univ. of Illinois.

HAMER, P., JACKSON, J., and THURSTON, F.F. (1961), *Industrial Waters Treatment Practice*, Butterworths & Co. (Publishers) Ltd., London.

HOWARD, F.H., NA CHIANGMAI, P., and PHIANCHAROEN, C., (1966), Ground Water Resources Development of Northeastern Thailand, *Ground Water Bulletin No.2*, *Ground Water Division, Department of Mineral Resources, Ministry of National Development*, Bangkok.

JUST, G. (1908), Kinetische Untersuchung der Autooxydation des Ferrobicarbonates, *Z. Phys.Chem.*, v. 63, pp. 385.

LONGLEY, J.M., ENGELBRECHT, R.S., and MARGRAVE, G.E. (1962), Laboratory and Field Studies on the Treatment of Iron-Bearing Waters, *J. Am. Wat. Wks Ass.*, v. 54, pp. 731-745.

MINZ, D.M. (1964), Aids to Coagulation, General Reports and Papers on Special Subjects, *Sixth Congress International Wat. Supply Ass.*, Stockholm.

RIDDICK, T.M. (1961), Zeta Potential and its Application to Difficult Waters, *J. Am. Wat. Wks Ass.*, v. 53, pp. 1007-1030.

SAWYER, C.N. (1960), *Chemistry for Sanitary Engineers*, McGraw-Hill Book Company, Inc., New York.

SIENKO, M.J., and PLANE, R.A. (1961), Chemistry, McGraw-Hill Book Company, Inc., New York.

STUMM, W., and LEE, G.F. (1961), Oxygenation of Ferrous Iron, Industrial and Engineering Chemistry, v.53, pp. 143-146.

SHAPIRO, J. (1964), Effect of Yellow Organic Acids on Iron and Other Metals in Water, J. Am. Wat. Wks Ass., v. 56, pp. pp. 1062-1082.

UNITED STATES PUBLIC HEALTH SERVICES (1961), Drinking Water Standards, 1961, J. Am. Wat. Wks Ass., v. 53, pp. 935-945.

WILLEY, B.F. and JENNINGS, H. (1963), Iron and Manganese Removal with Potassium Permangante, J. Am. Wat. Wks Ass., v. 55, pp. 729-734.

WORLD HEALTH ORGANIZATION (1963), International Standards for Drinking-Water, 2nd ed., World Health Organization, Geneva.

APPENDIX A

Table A 1 - Data on Calibration Curve of Iron Content in Water by Spectrophotometer

mg Fe x 10^{-2}	% Transmission
0.5	96.0
1.0	88.5
1.5	81.0
2.0	80.0
2.5	75.0
3.0	69.0
3.5	63.0
4.0	57.0
4.5	54.0
5.0	53.0
5.5	47.5
6.0	45.0
6.5	39.0
7.0	37.0
7.5	36.5
8.0	33.0
8.5	31.5
9.0	28.0
9.5	26.5
10.0	23.0
11.0	21.5
12.0	19.0

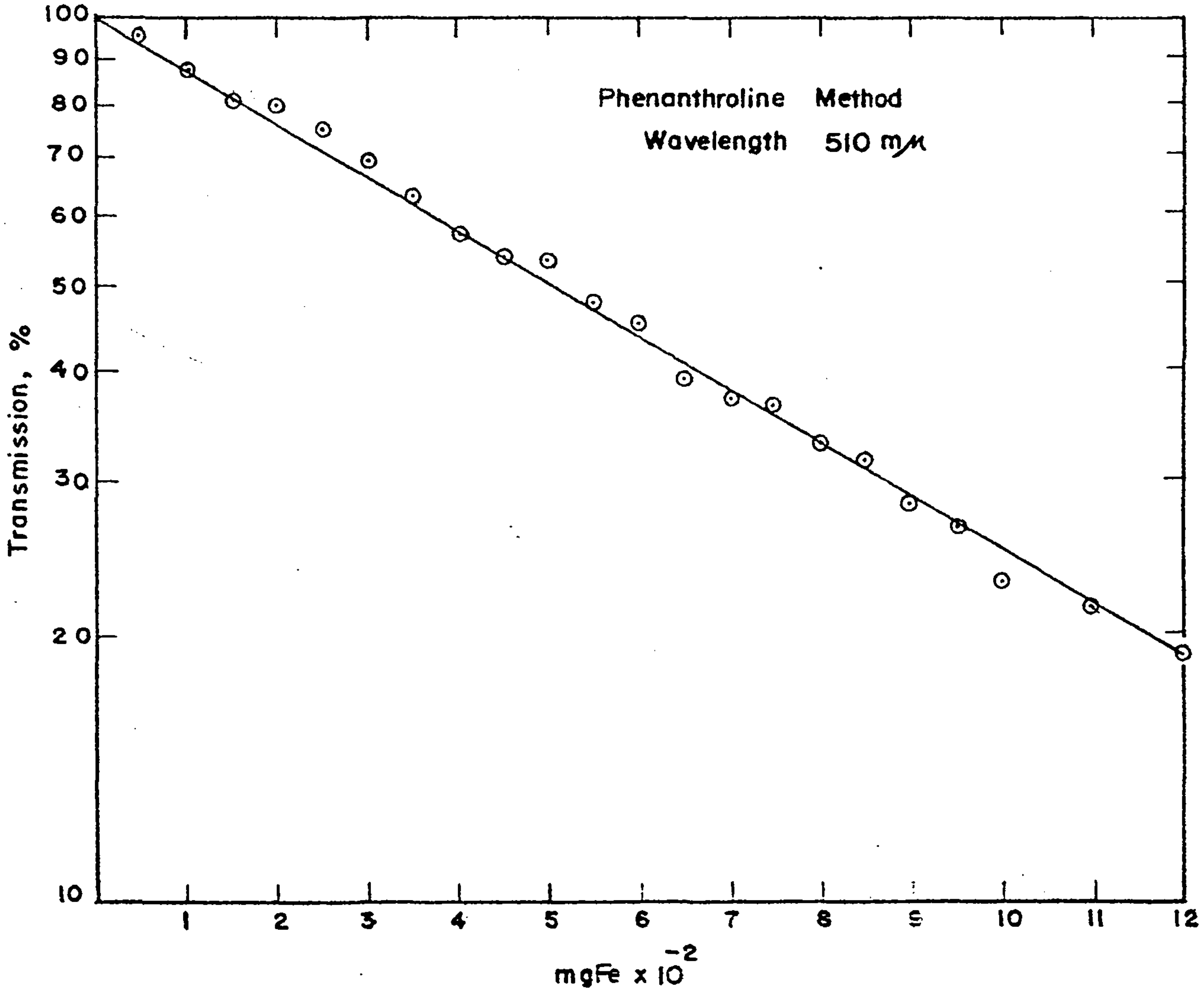


Fig. A-1 Calibration Curve for Iron.

APPENDIX B

Table B 1- Iron Concentration in Ground Water in Thailand from Division of Ground Water, Department of Mineral Resources, Minsitry of National Development.

City	Well number	Depth ft.	Total Fe mg/l	CO_2 mg/l	pH	Total hardness as $CaCO_3$ mg/l
Loei						
A. Chiengkan	J 27	125	3.5	20.0	7.2	300
A. Chiengkan	C 55	107	1.5	18.0	7.2	108
A. Talee	J 17	160	36.0	26.0	7.4	264
A. Talee	J 12	125	9.0	28.0	7.2	434
A. Talee	J 18	100	29.0	46.0	7.2	796
A. Maung	F 99	131	2.0	22.0	7.3	152
A. Maung	J 3	147	17.0	48.0	6.9	1334
A. Wangsapung	C 43	191	10.0	14.0	7.7	300
A. Sri-than	B102	112	21.0	79.0	7.0	350
Udorn						
A. Banpae	E156	100	23.0	3.0	7.2	2212
A. Nongbua -lampu	A122	180	3.5	62.0	7.1	320
A. Nongbua -lampu	A109	255	14.0	14.0	7.5	220
A. Noansang	A116	175	16.0	40.0	7.3	300
A. Noansang	A112	300	12.00	65.0	6.3	250
A. Kumpwapee	A 78	165	6.4	35.0	6.4	250
A. Kumpwapee	A 77	250	6.5	15.0	6.7	2155

City	Well number	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
A. Maung	A 99	515	0.8	9.0	7.1	9674
A. Pen	A138	125	11.0	3.0	7.4	2370
A. Bandung	E160	105	11.0	3.0	8.4	88
A.Maung	A117	510	0.0	12.0	6.8	7700
A. Nongharn	A103	120	20.0	15.0	7.2	680
A. Nongharn	A 93	150	11.0	77.0	6.8	789
<u>Khon Kaen</u>						
A. Chumpae	B104	158	5.0	4.0	8.1	130
A. Chumpae	B101	240	4.0	6.0	8.0	166
A. Chumpae	F126	110	8.0	43.0	7.4	464
A. Phuwieng	F139	109	6.0	2.0	8.2	220
A. Phuwieng	F141	90	5.6	2.0	8.0	262
A. Arjsamarch	B 90	140	6.9	4.3	7.9	552
A. Arjsamarch	B 88	260	5.2	44.0	7.1	380
A. Nongrae	F173	330	7.0	17.0	7.6	160
A. Nampong	A 76	255	15.0	47.0	7.8	200
A. Nampong	A 68	100	1.2	10.0	7.7	300
A. Kranuan	F 180	100	0.0	48.0	7.0	320
A. Kranuan	A 72	255	7.5	6.0	7.9	100
A. Maung	C 60	351	3.5	4.0	8.1	500
A. Maung	C 29	335	0.2	24.0	7.4	294
A. Banphai	C 24	244	1.0	7.0	7.8	799

City	Well number	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
A. Banjakri	F 152	100	0.64	20.0	7.6	466
A. Pol	F 52	253	17.0	1.0	8.4	122
A. Nongsonghong	F 51	155	3.0	4.0	7.3	2155
<u>Chaiyapum</u>						
A. Kaset - -somboon	B 95	170	3.0	37.0	7.0	
A. Kaset - -somboon	B 94	110	5.5	16.0	7.5	1120
A. Phukhiew	C 40	1004	3.5	39.0	7.3	1500
A. Phukhiew	B100	345	10.0	14.0	7.2	1645
A. Kaengkraw	P 59	150	2.4	86.0	6.9	656
A. Kaengkraw	P 53	120	7.6	117.0	6.8	224
A. Konswan	D 89	200	2.0	10.0	7.4	420
A. Maung	P 40	135	2.0	8.0	7.3	250
A. Saturus	C 77	100	2.8	28.0	6.3	12600
A. Saturus	C 78	400	5.5	53.0	7.0	1002
A. Bamned - narong	G 44	100	-	131.0	6.5	5400
A. Bamned - -narong	G 42	110	2.5	52.0	6.9	405
A. Bamned - -narong	G 38	645	2.8	32.0	7.1	240
A. Bankhuaw	C 81	191	4.5	22.0	7.5	200
<u>Sakonnakorn</u>						
Ban Khok - -Si School	A 88	200	8.0	17.0	7.1	1680
Wat Ban -Khok Si	A 87	480	3.2	29.0	7.1	803
A. Uthum -Phonpisai	B 28	346	5.0	60.0	7.1	476

City	Well number	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
Ban Sai Mun School	B137	50	6.0	31.0	7.4	1010
Ban Mon School	F 24	100	0.0	8.0	7.4	1000
A.Waritcha -phum	F 29	160	0.2	24.0	6.9	200
A.Waritcha -phum	B110	200	1.0	22.0	7.6	532
Wat Thep -Wong Saram	B113	70	10.0	6.0	6.9	241
Ban Na Muang	F 31	100	2.0	2.0	7.6	50
A.Wanonniwat	A 52	250	13.0	88.0	6.8	483
A Punnanikom	F 19	119	4.0	4.0	7.3	538
Ban Phak Kham -Phu Public Area	A 90	150	1.5	3.0	8.1	139
Ban Nong Suan -Public Area	B200	375	0.26	1.0	8.6	60
Ban Sang Kho	F 7	775	2.8	0	8.5	90
Wat Ban Nong -Krabok	B130	110	1.2	7	7.1	70
Ban Phom -Yai School	B127	110	5.0	66.0	6.9	210
Wat Ban Khok -Sung	B208	100	23.0	7.0	7.6	380
Ban N.Ramai	G 8	250	8.0	60.0	6.9	270
A Kusuman	G 7	1045	0.0	66.0	6.5	808
Ban A-Kat Public Area	B118	100	3.0	21.0	6.8	91
Ban Phon -Ngam	B153	75	4.0	4.0	7.5	460
A.Wanonniwat	A 56	260	11.4	22.0	5.9	4445
Banchampa Dong Public Area	B.116	75	6.0	21.0	5.9	52
A.Wanonniwat	F 32	100	1.0	16.0	7.4	222

City	Well No.	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
Nakornpanom						
Ban Sam Kha	G 24	75	8.0	15.0	6.6	60
Ta Lad Kae/ Highway Sect.	C 10	845	11.0	12.0	7.2	3414
Ban Dong Sawang	B186	105	28.0	28.0	7.0	160.0
A Maung	C109	65	4.0	48.0	6.1	40
Ban Nong -Na Saeng	C104	275	1.0	90.0	6.8	550
Wat Ban -Chieng Su	B128	150	1.0	34.0	7.0	298
Wat Maheson	C117	80	1.0	40.0	6.7	140
Ban Pla -Pak School	C113	85	1.0	29.0	7.1	310
Wat Ban -Phiman	B158	95	1.0	9.0	7.1	120
Ban Phon Tum Public Area	C122	85	2.0	84.0	5.8	357
500 m.S.E. of B.160NP.18	B160	150	70.0	13.0	7.4	140
A.Thapanom	G 20	95	12.0	72.0	6.5	170
A. Mukdaharn	G 28	85	1.4	7.0	7.9	310
A.Kham-Cha-I	B175	135	15.0	3.0	5.2	64
Wat Ban Thum -Wan	B178	100	0.0	26.0	7.3	216
Lum Phraphleng Canal Const.	G120	100	0.0	20.0	7.4	222
Kalasin						
Ban Hin Lat School	K 9	105	12.0	82.0	6.8	180
Ban Wan Public Area	K 19	100	2.0	6.0	7.9	240
Huai Phung Self-Help Settlement	K 24	105	6.0	31.0	7.2	238

City	Well No.	Depth ft.	Total Fe mg/l	CO_2 mg/l	pH	Total hardness as $CaCO_3$ mg/l
Ban Don Hua -Kha	K 16	100	6.8	37.0	7.3	252
Ban Nong -Saeng Public Area	D122	90	18.0	7.0	7.1	70
Huai Phung Self-Help Settlement	K 28	100	1.2	6.8	6.8	60
- do -	K 29	85	7.0	1.0	8.1	72
A. Sahat Khun	K 31	200	0.06	4.0	7.9	212
A Sahatkhun	D 46	526	10.0	22.0	5.5	24
Ban Nong -Pha Om	D 45	129	4.9	10.0	7.6	202
Wat Ban Nong So	C100	100	12.0	60.0	6.9	260
Ban Khok Si	D 37	128	4.4	19.0	7.5	210
A.Kamalasai	G 59	100	29.0	0.0	5.7	157
Wat Ban -Kabak	K 52	60	8.2	24.0	7.0	342
Ban Kaeng-Am Highway Sect.	F 6	510	18.0	124.0	5.5	86
Ban Nawi Public Area	K 15	120	1.0	0.0	7.3	38
Huai Phung Self Help Settlement	K 27	100	31.0	86.0	6.5	176
Ban Phon Thong	D 43	165	16.0	12.0	6.5	20
Kalasin Govt. Off.	D 39	118	11.0	1.2	7.9	46
A. Kalasin	G 58	230	41.0	8.0	5.2	50
Ban Nong Saeng Public Area	D122	90	18.0	7.0	7.1	70
Ban Nawi Public Area	K 15	120	1.0	0.0	7.3	38
Huai Phung Self Help Settlement	K 28	100	1.2	24.0	6.8	60

City	Well No.	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total Hardness as $CaCO_3$ mg/1
Roi-ed						
A. Pontong	D 136	200	1.6	45.0	6.7	346
A. Archsamat	D 113	255	2.0	16.0	7.3	540
A. Salapume	D 21	111	2.8	7.0	7.5	986
A. Salapume	D 139	90	4.8	92.0	5.8	48
A. Salapume	D 133	100	1.0	130.0	6.3	285
A. Suwannapume	D 110	150	4.0	6.0	6.7	160
A Jaturapuk-piman	D 11	300	4.0	124.0	6.4	153
A. Jaturapuk-piman	D 107	100	5.0	13.0	7.2	448
A. Maung	D 104	200	4.4	17.0	7.4	136
A. Maung	D 24	130	5.0	626.0	6.2	180
A. Maung	D 105	200	7.0	9.0	6.9	70
A. Tawachaburi	D 130	200	5.0	7.0	7.0	4439
Mahasarakam						
A. Maung	D 57	80	0.02	3.0	7.9	2000
A. Maung	D 27	129	10.0	13.0	7.3	420
A. Maung	D 99	200	20.0	7.0	7.9	200
A. Maung	D 55	104	4.0	4.0	7.2	40
A. Wape Patum	D 50	198	3.5	13.0	7.2	920
A. Wape Patum	D 54	137	12.0	61.0	7.0	790
A. Payakka-pumpisai	C 96	150	11.0	9.0	7.6	308
A. Nang Chaek	C 88	400	1.5	1.0	8.2	60

City	Well No.	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
A. Chieng Yaen	G 49	200	8.7	215.0	6.1	852
Wat Ban Kho	G 54	150	4.0	2.0	8.6	90
A.Kosompisai	D 68	260	4.8	6.0	7.3	83
A.Kosumpisai	D 70	205	12.0	2.0	8.4	90
A.Kosumpisai	D 98	200	14.0	58.0	7.1	110
Wat Ban Nong -Nae	D 65	500	13.0	3.0	8.2	130
Wat Ban Dong	C 93	300	0.12	13.0	7.4	48
Wat Ban Nong -Bua Santu	C 94	300	11.0	4.0	7.4	495
<u>Nong Khai</u>						
A. Srichieng -Mai	A163	130	5.0	48.0	6.3	12
A. Srichieng -Mai	A160	110	12.0	12.0	5.2	0
A. Srichieng -Mai	A 68	100	1.2	10.0	7.7	300
A. Srichieng -Mai	A157	110	5.0	24.0	6.4	44
A Thabo	A177	115	5.0	44.0	7.0	296
A Thabo	E142	155	6.8	60.0	5.8	38
A Maung	A154	105	12.0	33.0	6.8	560
A Maung	E 20	160	9.8	44.0	6.9	312
A Maung	A175	155	0.0	5.0	8.2	176
A Maung	A151	105	0.0	3.0	8.2	188
A Maung	A172	155	0.0	0.0	8.4	152
A Maung	F 65	100	14.0	0.0	8.1	1164

City	Well No.	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
A. Maung	F 69	100	10.0	134.0	6.7	320
A Bungkan	A134	160	3.0	10.0	6.9	40
A Srichieng-Mai	A155	100	4.0	1.0	7.8	60
Ban Don Va Nang	A132	300	21.0	3.0	7.8	720
Ban Hua Rat	A136	200	1.0	17.0	7.1	390
Surin						
A.Chumpolburi	C140	67	0.6	144.0	5.7	26
A. Nongtum	A 18	301	2.0	36.0	7.5	1290
A. Rattana-buri	C148	500	15.0	7.0	7.9	176
A. Rattana-buri	C149	80	6.2	36.0	6.4	56
Ban Tha Sila School	A 17	438	16.0	0.0	8.2	192
A.Jom Phra	A 24	1031	1.8	76.0	6.8	532
A.Jom Phra	A 17	142	5.6	7.0	7.8	842
A Maung	A 4	405	18.3	21.0	7.0	594
A Samrongtab	C166	100	9.0	0.0	8.5	2800
A. Sangkha	C157	120	7.0	12.0	7.7	212
A Sangkha	C156	75	4.0	6.0	7.3	262
A Prasat	C125	150	4.0	29.0	7.2	55
A. Prasat	C124	150	1.8	2.0	7.3	62
Burirum						
A Pakonchai	B 18	120	4.8	36.0	6.8	196
A Pakonchai	B 15	101	16.0	19.0	7.4	94

City	Well No.	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
A Nangrong	B 20	105	3.0	15.0	8.0	72
A Nangrong	B 21	255	4.0	52.0	7.0	408
A Maung	B 23	180	2.5	111.0	6.9	376
A Maung	B 24	513	6.3	3.3	7.5	50
A Maung	B 10	100	5.6	60.0	7.0	340
A Krasang	B 26	271	3.5	44.0	7.3	696
A Satuk	B 25	1015	10.0	60.0	6.1	576
A Krasang	B 27	94	4.2	6.0	7.4	461
<u>Srisaket</u>						
A Utumpornpi-sai	B 31	301	4.0	4.4	7.5	1860
A Maung	B 42	356	0.5	39.0	7.1	618
A Rasisai	C198	130	6.0	24.0	6.3	2386
A Prangku	C170	100	0.5	5.0	7.8	1115
A Khukhun	C176	240	11.0	6.0	7.4	3380
A Khukhun	C179	130	9.0	6.0	7.0	46
A Kanthara-lak	B 38	125	10.0	3.8	7.0	1950
A Kanthara-lak	B 39	176	2.5	49.0	6.9	1316
A Kanthara-lak	C196	130	14.0	1.0	8.1	72
A Khukhun	C182	100	6.6	10.0	7.8	160
<u>Nakorn - Rachasima</u>						
A Buayai	C 84	253	0.0	109.0	6.4	3780
A Buayai	E 45	55	24.0	54.0	7.0	4900

City	Well No.	Depth ft.	Total Fe mg/1	CO_2 mg/1	pH	Total hardness as $CaCO_3$ mg/1
A Pratai	C 17	375	10.0	67.0	7.0	3600
A Chumpuang	D 77	405	1.2	53.0	6.9	2700
A Pimai	D 74	180	0.8	219.0	6.1	2654
A Jakaraj	G114	300	16.0	12.0	7.4	228
A Maung	H 11	245	8.5	16.0	7.3	348
A Maung	Q 3	215	0.0	17.0	7.1	144
A Maung	H 4	145	2.0	3.0	8.2	100
A Chokchai	D 73	345	1.0	9.0	7.5	1205
A Pakthongchai	D156	190	1.0	31.0	7.1	400
Nakornracha-sima						
A Pakthongchai	G121	298	1.0	44.0	6.4	2814
A Pakchong	P 10	75	4.5	52.0	7.1	684
A.Pakchong	P 22	150	7.0	300.0	6.5	390
A Pakchong	P 18	101	0.0	135.0	6.7	859
A Sekeui	P 12	800	7.0	4.0	8.1	180
A Sungnern	A 65	170	5.9	520	7.2	222
A Dankhuntot	F 44	100	116.0	7.0	7.3	1202
A Noanthai	G 1	1465	7.7	26.0	7.3	1100
A Noanthai	G 35	1500	0.0	3.0	7.4	150
A Kong	D 81	100	0.0	35.0	6.1	2200
A Kong	D 82	150	0.0	3.0	8.0	306
A Nensuang	B 80	100	0.0	70.0	6.6	1900

City	Well No.	Depth ft.	Total Fe mg/l	CO_2 mg/l	pH	Total hardness as $CaCO_3$ mg/l
Ubol						
A. Laeng-Nokta	B 75	300	4.0	31.0	7.2	158
A. Laeng-Nokta	G 99	100	0.0	17.0	6.5	5200
A. Khemraj	A 50	310	3.5	22.0	6.6	370
A. Khong Jeam	L 12	165	14.0	12.0	8.4	48
A.Pibulmungsa-harn	B 55	125	0.5	111.0	6.5	158
A.Dej-Udom	G 65	125	1.0	5.0	7.6	90
A.Warin-Chamrap	B 50	400	0.01	1.6	7.7	134
A.Warin-Chamrap	G 61	65	4.4	63.0	6.4	16
A.Khaengnai	A 35	435	6.5	15.0	6.5	40
A.Kam Khaen-Keo	A 38	105	6.0	14.0	6.4	53
A.Yasotorn	A 44	1010	5.0	156.0	6.0	98
A.Amnaj-chareon	F 79	100	7.5	235.0	6.1	240
A.Amnaj-chareon	F 77	60	3.0	55.0	6.7	165
A.Amnaj-chareon	F 80	150	0.2	73.0	6.9	92
Song Khla						
A. Had Yai	H 42	-	2.0	12.0	6.1	40
A. Maung	H 43	90	1.2	9.0	7.4	250
Thai Marine-Food Co.	H 45	200	90.0	15.0	5.8	12
A Had Yai	H 46	-	1.9	20.0	5.6	20
Songkhla Dept. of Trans. Kho Neng	H 48	200	8.0	12.0	7.2	144
A Muang	H 49	50	5.0	5.0	8.0	104

City	Well No.	Depth ft.	Total Fe mg/l	CO_2 mg/l	pH	Total hardness as $CaCO_3$ mg/l
4th Mineral Resource Centre	H 50	170	17.0	6.0	6.4	1072
A. Ranot	H 51	240	63.0	30.0	7.3	374
A. Ranot	H 52	410	13.0	30.0	7.2	276
Uttaradit						
A. Nam Pat	K 33	250	39.0	2.0	8.1	104
A. Nam Pat	K 34	50	9.0	25.0	6.8	92
Ban Pha Luat	G 70	150	130.0	3.0	7.9	76
Ban Wang Hua Doi	G 69	100	40.0	2.0	7.9	82
Prachinburi						
Klong Nam Sai Self Help Settlement	Q 8	150	7.0	35.0	7.4	120
Ban Nong Phu	Q 11	80	2.2	40.0	7.3	396
A. Ta Phraya	Q 13	215	2.4	11.0	7.1	248
A. Taphraya	Q 15	150	2.8	107.0	7.0	264
A.Aranyapra-thet	Q 18	150	0.0	41.0	7.1	216
A.Aranyapra-thet	Q 20	88	2.8	5.0	8.0	200
Chakkraphong Army Camp	Q 25	95	1.8	3.0	7.0	24
Bandong Khilek Public Area	Q 29	150	0.1	5.0	7.7	140
Wat Phrom Senaram	Q 36	150	6.0	17.0	7.4	352
Nakorn Nayok						
Ban Na Police Station	Q 38	125	6.5	0.0	8.9	28

City	Well No.	Depth ft.	Total Fe mg/l	CO_2 mg/l	pH	Total hardness as $CaCO_3$ mg/l
Ban Phrik Health Centre	Q 39	320	1.0	5.0	7.4	410
Ban Koka To	Q 42	250	9.0	7.0	7.3	220
A. Pakphli	Q 43	110	8.0	23.0	6.5	2320
Khao Cha -Ngok Army Camp	Q 41	80	3.0	6.0	6.9	8
<u>Saraburi</u>						
A. Phraputabat	E 55	20	0.0	24.0	7.4	480
A. Phraputabat	E136	150	2.0	10.0	7.7	260
A. Phraputabat	F137	100	42.0	22.0	7.3	50
A. Kaeng Koi	P 68	150	0.4	11.0	7.8	198
A Maung	P 64	120	1.0	2.0	8.5	12
A. Uiharn -Daeng	-	258	0.45	-	6.8	80
A. Nong Kae	-	113	1.0	-	6.5	960
A. Nong Kae	-	183	0.04	-	8.0	420
<u>Petchaboon</u>						
A. Maung	E 83	113	20.0	3.0	8.2	153
A. Maung	E 81	140	21.0	17.0	7.2	130
A. Nong Phai	E 73	152	8.0	34.0	7.1	269
A. Wichienburi	E 66	113	5.5	19.0	7.6	618
A.Wichienburi	E 88	308	5.0	118.0	6.6	47
A. Maung	-	157	0.6	-	7.0	450
A. Klomsak	-	350	1.7	-	7.4	228
A. Chondaen	-	157	2.0	-	7.1	2200

APPENDIX B

Table B2 - Iron Concentration in Ground Water of Thailand from Department of Public and Municipal Works, Ministry of Interior.

City	Well No.	Depth ft.	Total Fe mg/l	pH	Total hardness mg/l $CaCO_3$
<u>Sukho-thai</u>					
A.Sawankaloke	178/2-08	98	2.3	7.3	248
A.Srisatchanalai	128/2-07	60	1.8	6.6	480
A.Srisamrong	152/26-07	260	0.6	7.2	94
A.Maung	147/21-07	169	1.3	7.2	126
A.Maung	136/6-07	145	3.3	7.7	85
<u>Phitsanuloke</u>					
A. Maung	208/32-08	188	1.8	7.2	320
A. Maung	213/37-08	240	4.8	7.1	102
A. Maung	221/45-08	185	5.8	6.8	98
A. Maung	190/14-07	215	5.8	6.8	205
A. Bangkatum	191/15-07	270	5.3	6.8	208
<u>Nakhorn Sawan</u>					
A. Maung	168/42-07	287	6.5	6.6	132
A. Maung	175/49-07	285	5.5	6.9	1500
A. Maung	K 32	95	12.0	8.1	116
A.Banpotwisai	207/31-08	241	8.2	-	-
A.Banpotwisai	216/40-08	267	4.4	-	-
A.Payukhakeri	145/19-07	131	0.8	7.3	450

City	Well No.	Depth ft.	Total Fe mg/l	pH	Total hardness mg/1 $CaCO_3$
Singh-buri					
A. Maung	14/13-03	170	1.0	8.0	321
A. Phromburi	294/18-10	214	0.2	7.0	402
A. Bangrajun	283/7-10	312	0.2	7.2	216
A. Tachang	283/9-10	354	0.4	8.3	220
Kanchana-buri					
A. Maung	171/44-07	113	0.2	-	-
A. Tamaka	173/46-07	215	0.9	7.9	148
A. Tamaung	55/12-03	193	2.5	7.3	164
A. Panomtaun	64/4-05	155	1.2	7.0	1200
A. Panomtaun	139/12-07	150	2.8	8.4	80
Supanburi					
A. Songpenong	87/44-05	187	1.4	8.1	136
A. Don-jedi	13/12-03	178	1.3	8.0	212
A. Utong	17/16-03	152	2.5	6.5	2100
A. Utong	230/9-09	144	5.0	7.5	850
Ayudhaya					
A. Maung	30/7-04	123	0.3	7.1	158
A.Wangnoi	88/45-05	350	0.2	-	-
A.Bang Pa-Hun	293/17-10	300	1.0	7.3	220
A. Bang Pa-in	249/28-09	565	0.2	-	-

City	Well No.	Depth ft.	Total Fe mg/l	pH	Total hardness mg/l $CaCO_3$
A. Tarae	24/1-04	167	1.0	7.4	2140
A. Tarae	26/3-04	167	0.3	7.2	1220
<u>Pathum-thani</u>					
A. Maung	311/35-10	248	0.8	7.5	542
A.Thunga-buri	279/3-10	364	0.4	8.7	32
A.Klong-luang	286/10p10	248	0.4	8.1	102
A.Klong-Luang	289/13-10	312	0.2	8.4	106
<u>Ratburi</u>					
A. Maung	211/35-08	131	0.2	7.3	325
A.Potharam	206/30-08	660	0.8	7.0	267
A.Paktho	146/21-07	221	0.8	7.7	550
A.Paktho	139/13-07	300	1.8	6.9	350
A.Damnernsaduak	155/29-07	213	1.3	7.4	1100
<u>Angthong</u>					
A. Swaeng-ha	307/30-10	112	0.2	-	-
A. Chaiyo	325/49-10	174	0.1	-	-
<u>Samutprakan</u>					
A. Maung	-	760	0.5	7.3	134
A. Maung	H 29	903	11.0	6.9	312
A Prapadaeng	H 31	403	5.0	8.1	280
A Prapadaeng			4.3	7.9	2350

City	Well No.	Depth ft.	Total Fe mg/l	pH	Total hardness mg/l $CaCO_3$
Cholburi					
A. Banglamung	125/2-06	141	1.0	8.5	72
A. Banglamung	103/5-06	136	2.4	7.7	280
A. Banglamung	133/7-07	141	0.3	8.2	20
A. Panthong	131/5-07	160	1.3	7.4	174
Rayong					
A. Maung	203/27-08	84	0.8	7.2	280
A. Maung	205/29-08	80	1.0	7.1	53
A. Maung	151/25-07	45	2.9	5.9	80
A. Bankhai	149/23-07	67	3.3	6.2	17
A. Bankhai	150/24-07	53	1.3	5.7	80
Chanthaburi					
A. Khlung	144/18-07	74	1.2	6.3	40
A. Khlung	137/11-07	75	0.8	5.0	2
Pichit					
A. Tapanhin	163/37-07	215	2.3	7.8	136
A. Tapanhin	140/14-07	150	1.3	-	-
A. Tapanhin	181/5-08	310	0.8	-	-
Chainat					
A. Sanphraya	238/17-09	91	0.7	7.2	302
A. Sanphra-ya	241/20-09	92	0.4	7.0	451
A. Sanburi	243/22-09	232	0.6	7.4	234

	Well No.	Depth ft.	Total Fe mg/1	pH	Total hardness mg/1 $CaCO_3$
Prae					
A. Maung	142/16-07	246	2.3	7.0	168
A. Sung-men	220/49-08	368	0.1	7.2	148
A. Maung	232/11-09	400	0.1	7.0	210
Cha-choengsao					
A.Bangpakong	100/11-06	295	1.8	7.1	148
A.Bangpakong	20/20-03	500	3.8	7.3	210
Prachaupkhirikhun					
A. Maung	91/2-06	750	0.3	7.4	146
A. Hua Hin	H 34	140	0	7.3	1528
A. Pranburi	-	317	1.0	7.4	940
Wat Ban NongKae	K 37	100	33.0	8.0	2640
Nakhornpathom					
A.Kampaengsaen	218/42-08	350	0.1	7.5	168
A. Maung	200/24-08	302	0.4	7.2	400
A. Maung	191/15-08	307	0.7	7.9	497
A. Maung	195/19-08	645	0.1	7.6	480
Nondhaburi					
A. Maung	130/4-07	720	1.3	7.4	174
A. Pakred	129/3-07	565	1.0	7.1	220
A. Pakred	82/93-05	530	3.0	7.4	340
A. Pakred	119/30-06	567	2.1	7.1	219

City	Well No.	Depth ft.	Total Fe mg/1	pH	Total hardness mg/1 $CaCO_3$
Phetburi					
A. Maung	H 32	850	17.0	7.1	1440
A. Khao-yoy	H 33	200	2.0	7.0	2044
A. Banlam	13/14-03	512	0.3	7.6	620
A. Banlam	11/10-03	685	0.5	7.0	644
Samutsakorn					
A. Kathumban	89/56-05	540	0.3	7.3	197
A. Kathumban	212/36-08	355	0.1	7.1	382
A. Kathumban	215/39-08	542	1.8	7.5	2192
A. Kathumban	210/34-08	450	1.6	7.5	174
Dhonburi					
A.Pasijareon	24	481	0.7	8.4	455
Wat Tongtamachart	12	580	0.5	7.5	173
Wat Panurangsri	9	530	0.2	7.6	98
Wat Chimtayigawat	20	580	1.0	8.2	154
Wat Craewan	19	552	0.2	8.1	140
Wat Warurachin	6	670	1.2	7.8	484
Wat Nang	34	546	4.8	7.3	523
Wat Porieng	10	559	1.7	7.3	214
Soi Benja	23	520	0.7	8.4	127
Sapan Put	11	580	0.1	8.2	98
Klong san	1	552	0.3	7.4	158

City	Well No.	Depth ft.	Total Fe mg/1	pH	Total hardness mg/1 $CaCO_3$
Bangkok					
A. Sampantawong		713	0.9	7.4	513
A. Patumwan		-	1.0	7.6	403
A. Phranakorn		607	0.5	7.2	247
A. Phranakorn		597	0.5	7.2	195
A. Bangkhen		600	1.3	8.4	260
A. Bangkhen		570	1.3	7.9	126
A. Bangkapi		463	0.1	8.0	137
Average of overall chemical analyses from Chemical Analyses Section, Sam Sen Water Works		407 -669 (580)	0.0 -1.4 (0.7)	6.9 -7.6 (7.5)	90 -242

Note: A = Ampheur