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REMOVAL OF IRON FROM GROUNDWATER

(Thesis No. 838)

by

Hum Ke Siong

Asian Institute of Technology

Bangkok, Thailand

1975

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Hum Ke Siong

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For the Degree of Master of Science

Asian Institute of Technology

Bangkok, Thailand

834
1975

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by

Hum Ke Siong

A thesis submitted in partial fulfillment of the requirements for
the degree of Master of Science of the Asian Institute of Technology,
Bangkok, Thailand.

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ABSTRACT

The level of iron in AIT groundwater was of the order of 0.25 mg/l, which causes the groundwater to be sometimes aesthetically unacceptable. Thus the primary object of this study was to evaluate feasible alternatives to overcome the iron problem. In the first attempt, a pilot plant consisting of a tray aerator, chemical mixing chamber and upflow solids-contact precipitator was constructed in order to study its efficiency in iron removal. Firstly, evaluation was made on the efficiency of the tray aerator. 6-10 cm coke and charcoal were used as packing media and tested for efficiency of oxidizing and removing iron at three different dosing rates, 5, 10 and 15 l/sec-m². Coke was found to be a better medium than charcoal and at optimum conditions, it could bring about oxidation of 12% of the iron content and 20% removal at the dosing rate of 5l/sec-m². Accordingly, laboratory jar tests were performed to determine the optimum dosage of chemicals required for iron removal. Alum + NaOCl and lime + NaOCl were tried. This result served as a guide in the operation of the pilot plant. With the optimum conditions of aerator and jar tests, at least 60% of the iron was removed, leaving the finished water with iron in the range 0.06-0.09 mg/l, which had stabilized against iron settlement and colouration for 6 days upon re-chlorination. The second attempt was to study chemical addition for prevention of iron oxidation and settlement. Among the selected chemicals, sodium polyphosphate and silicate seemed to be the best but chemical costs would be high.

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TABLE OF CONTENTS

<u>CHAPTER</u>	<u>TITLE</u>	<u>PAGE</u>
	Title Page	i
	Thesis Approval	ii
	Abstract	iii
	Acknowledgements	iv
	Table of Contents	v
I	INTRODUCTION	1
	A. General	1
	B. Statement of Problem	1
	C. Purpose of Study	2
	D. Scope of Study	2
II	LITERATURE REVIEW	3
III	EXPERIMENTAL INVESTIGATION	11
	A. Design and Description of Equipment	11
	B. Procedure and Analytical Methods	11
	C. Jar Tests	13
	D. Operation of Pilot Plant	13
	E. Determination of the Best Chemical for Prevention of the Settlement of Iron in the AIT Groundwater	14
	F. Determination of the Optimum Concentra- tion of the Best Chemical to Produce the Desire Results	14
IV	PRESENTATION AND DISCUSSION OF RESULTS	16
	A. Physical and Chemical Characteristics of AIT Groundwater	16
	B. Investigation into the Efficiency of Aeration for Oxidation and Removal of Iron	17
	C. Preliminary Investigations with Jar Tests	23
	D. Investigation into the Efficiency of the Pilot Plant Treatment with 100 mg/l Lime	27
	E. Investigations into Efficiency of the Pilot Plant Treatment with 60 mg/l Alum	29
	F. Determination of the Best Chemical for Prevention of the Settlement of Iron in AIT Groundwater	33
V	CONCLUSION	39
	REFERENCES	41
	APPENDIX	43

I INTRODUCTION

A. General

It has been noted, for a long period, that iron creates serious problems in public water supplies. The problems are most extensive and critical with underground waters, but difficulties are also encountered at certain seasons of the year in water drawn from some surface waters.

The presence of iron in water causes what is commonly called "red water" which is actually the reddish brown colour of the hydrated oxidized iron. In addition, it may produce taste and odour. However, as far as is known, humans suffer no harmful effects from drinking water containing iron. Such water when exposed to the air become turbid and highly unacceptable from the aesthetic viewpoint, owing to the oxidation of iron which forms a colloidal precipitate or suspension. Besides, iron also interferes with laundering operations, imparts a taste and colour to water which is detectable at very low concentrations. For these reasons the W.H.O. (1971) International Drinking Water Standards limit the content of iron in public water supplies to the highest desirable level 0.10 mg/l.

Under reducing conditions in natural waters, particularly in most groundwaters, iron exists in the +II oxidation state which is a stable form of iron. But after contact with oxygen either by aeration or other means, the iron in these waters will undergo a change from the ferrous state to the ferric state, that is, in the +III oxidation state. Due to the relative insolubility of this stable form of iron in oxygenated waters, the concentration of soluble ferric iron is limited and imparts a colour to the water supply. Iron may also exist in water as organic complexes, which are formed by chelation of some negatively charged organic ligands to the iron which is in the centre position. They are hard to be oxidized by air oxygen because of the surrounding organic ligands which act as a protective shell.

The conventional method of iron removing treatment plant consists of three basic unit processes, namely, oxidation, sedimentation and filtration. The oxidation process is considered to be one of the most important parts of the treatment.

B. Statement of Problem

Groundwater supplied to the AIT campus is used with only disinfection by chlorine after pumping. The pumped water at the borehole contains relatively low concentrations of iron which, on chlorination, become oxidized and precipitate causing coloured water problem some days. Chlorination augments iron difficulties causing stains on plumbing

fixtures and on clothing, and deposits on food during cooking. It also produces a heavy accumulation of sludge in the water tower and deposits in mains. An iron removal plant would have provided a solution to the problems, but the undertaking might be expensive, particularly for a small water supply system as in the AIT campus.

C. Purpose of Study

The discolouration of the AIT groundwater supply is sometimes aesthetically unacceptable, thus the primary object of this study was to evaluate feasible alternatives to overcome the iron problems, and arrive at the most economical solution.

D. Scope of Study

The study was carried out in the following two main parts as stated:

Firstly, an attempt was made using a tray-type aerator as designed by LIMRAT (1968), to determine its efficiency in oxidizing and removing iron from AIT groundwater. The tray-type aerator was used because it was cheap to construct, operate and maintain. Subsequently, experimentation of the iron removal by aeration plus chemical treatment was performed and determined. Jar tests were carried out to determine the optimum dosage of the chemicals used. The pilot plant which consisted of a tray aerator, by-pass chamber and upflow solids-contact precipitator was then operated at all such optimum conditions, and the chemical and physical properties of both raw water and treated water, as well as the iron removal efficiency, were then determined.

The second part of the study was based on the investigation of whether there were some chemicals which could satisfactorily tie up the soluble iron originally present in the raw water, resulting in the elimination of the more conventional iron removal treatment, that is, aeration, sedimentation, followed by filtration. Investigations included:-

- (1) The best chemical for the AIT groundwater.
- (2) The optimum concentration of that chemical to produce desired results.

II LITERATURE REVIEW

OLDHAM and GLOYNA (1969) stated that the first approach to iron removal was put forward near 1850 when the study of dissolved iron in water was first gained importance. The research led to the development of the aeration and filtration process of removing iron from water supplies.

WESTON (1909) mentioned the difficulties which may be encountered in removing iron from groundwater. He divided iron bearing water into two categories, those which began to precipitate the iron immediately after aeration and those which hold at least a portion of the iron in solution indefinitely even after aeration. WESTON also believed that such difficulties were due to the particles of organic matter accumulated on the dispersed iron and preventing its coagulation.

Accordingly, many investigators have carried on studying the problems of iron removal from groundwater supplies, for example HALE (1916), COCK (1950), GHOSH (1965) and others. Whatever treatment method was employed, difficulties and incomplete iron removal was often encountered. Furthermore, it is rather unfortunate that not all water supplies respond to a simple method for iron removal, and more often than not, specific pilot testing of each water source would have to be carried out to determine the most economical method of iron removal.

BROWN (1952) reported on experimental work on the removal of carbon dioxide and iron with the use of six coke trays aerator and sand filtration at Memphis Tenn. The head loss from the top tray to the bottom was 2.70 m. (9 ft.). The sand filter 25 cm. (10 in.) square was constructed and the effluent from the aerator was filtered through it at the rate of 3.32 l/sec-m^2 (2 gpm/ft^2). Under normal operating conditions, the aerator dosing rate was $10.2/\text{sec-m}^2$ (15 gpm/ft^2). No lime was added in the treatment process. After filtration, it was found that only a trace amount of iron remained in the filtered water.

GHOSH, CONNOR and ENGELBRECHT (1966) studied factors that governed the kinetics of iron precipitation in natural groundwaters in order to find a more rational approach to the engineering design of reaction basins in iron removal plants. Each 8 litres of representative sample was aerated for 2 minutes to raise the dissolved oxygen 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 reaction 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. 2.1. As water samples were drawn from

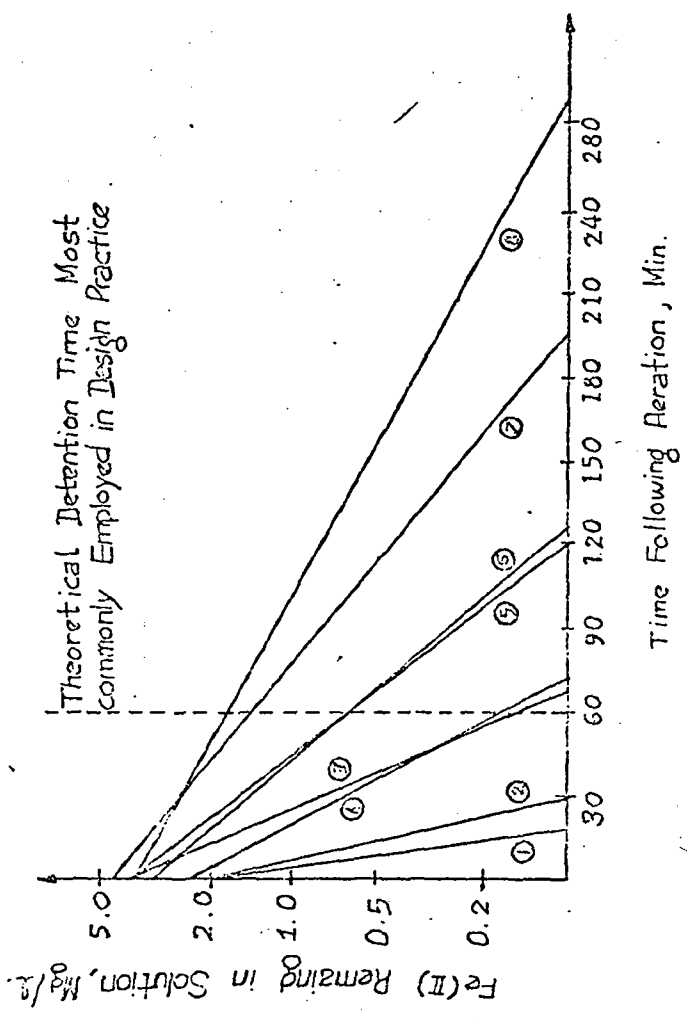


Fig. 2.1 Precipitation of Iron in Illinois Ground Waters after GHOSH et. al. (1966). ① to ⑧ Denotes Different Plant Locations

different sources with various pH values, it is clear that the use of a single specific reaction time for iron precipitation is not applicable for all groundwaters. A more suitable approach to the selection of a reaction time would be the direct measurement of the rate of iron precipitation. Furthermore, they also studied the effect of pH and alkalinity on the rate of iron oxidation. They found that higher values both in alkalinity and pH of water resulted in shorter half-life and more rapid precipitation rates.

A study of colour and iron removal was carried out by McCracken (1960) including both laboratory jar tests and pilot plant experimentation. The pilot plant consisted of five main units. These included a flow measurement device, chemical feeding apparatus, a flocculation tank, a sedimentation basin and a rapid sand filter column. Extensive jar tests were conducted in an attempt to determine appropriate chemical treatment. The following results were obtained using alum as the coagulant:-

(1) With the dosage of about 51 mg/l of alum a very good floc was formed and colour was lowered to 20 ppm and iron to 0.30 mg/l. Higher dosage of alum did not increase the colour removal and only served to increase the pH and increase the amount of residual iron.

(2) Slightly better results were obtained using liquid alum with a dosage of 3 ml/l, colour was reduced to 12 ppm and iron to 0.2 mg/l and a very good floc was formed. Unfortunately, when an investigation was made with the pilot plant he found that the pilot plant did not accomplish so acceptable a degree of iron removal as had been indicated by jar tests. It was further found that using chlorine as an oxidizing agent and lime for pH control, the iron content in the finished water was about 0.05 mg/l. The treatment of 9 mg/l of chlorine and 22 mg/l of lime was proposed and this produced a water with a pH quite close to the pHs indicated for corrosion control. He also stated this proposed method might be regulated within such limits that no post chlorination or other treatment of the finished water would be required.

Chlorine and hypochlorites are effective oxidizing agents and have been used to oxidize soluble ferrous iron to the insoluble ferric iron. Stoichiometrically 1 mg/l of chlorine will oxidize 1.6 mg/l of ferrous iron. However, more than theoretical quantities are usually required in practice. MATHEWS (1947) reported that iron removal could be effected by free residual chlorine at normal pH values. His results are shown in Table 2.1.

Table 2.1 - Removal of Iron with Free Residual Chlorination

Sample	Raw, mg/l	Contact, mg/l	Settled, mg/l	Filtered, mg/l
Chlorine residual	0	0.56	0.50	0.46
Chloramine residual	0	0.09	0.09	0.07
Iron	3.5	2.00	1.60	0

BOLAS (1965) described the use of catalytic blankets in a upflow sedimentation tank for iron and manganese removal; his plant consisted of an aerator, a contact tank, three upflow sedimentation tanks equipped with continuous sludge bleeds from the top of the sludge blanket and oxidizing filters. Lime was used as a coagulant and it was applied at two consecutive points between the aerator and the upflow sedimentation tanks. No coagulant aid was found to be needed to form the blanket in the tanks. It was reported too that sufficient dissolved oxygen was found at all stages. The plant was capable of removing iron completely even when the iron content of the raw water exceeded 15 mg/l.

LIMRAT (1968) studied the efficiency of a tray aerator, under variable conditions in oxidizing and removing iron, followed by an investigation into the use of the upflow solids-contact precipitator in iron removal. A pilot plant which consisted mainly of an aerator and an upflow solids-contact precipitator was designed and constructed. Coke, 6.35-11.42 cm in size, was found to be the most efficient aerator medium. With such size of coke, the percentage of iron removal (for the initial level of total iron 8-10 mg/l) were found to be 16% and 11.5% respectively. He further investigated the efficiency of the pilot plant for the iron removal with optimum conditions of the aerator and various dosages of alum + lime. The results obtained indicated that the upflow solids-contact precipitator with no preformed sludge blanket, could not work satisfactorily in removing iron until a sufficient depth of sludge was developed. With a preformed sludge blanket, the precipitator could remove iron efficiently within the third hour of operation.

Thus far the previous discussed methods, some of them sometimes required an expenditure of funds that the municipality felt it could not afford to spend. As stated by DART and FOLEY (1970), even a simple aeration plant could cost \$44,000 per million litres daily (\$200,000 per mgd.) as a capital investment. They also mentioned that the finished waters could have anywhere from 0.3 to 1.0 mg/l iron, such waters appeared to be quite acceptable to consumers; thus it is possible that the AIT groundwater problem may be overcome by preventing its iron precipitation during chlorination. In other words, the iron content of the water at all points held, as nearly as possible to the level originally present in the well water.

Prevention of the settlement of iron can be achieved by two methods, namely, the control of chlorine dosage at such a level that it will not oxidize the ferrous iron but at the same time the disinfection effect must be maintained; and the addition of chemicals to withhold the iron so that no precipitation will take place, the chemical added must harmless to consumers.

HENRY (1950) studied the prevention of settlement of iron in groundwater supplies. The typical well water analysis is shown in Table 2.2. Some results of his tests are shown in Figs. 2.2 to 2.5. He reported that the recommended rate by RICE and OWEN (1947) of application of twice as

Table 2.2 - Typical Well Water Analysis

pH	7.2-7.3
Colour	5-15
Temperature, °F	76
Turbidity, JTU unit	0
Ammonia Nitrogen, mg/l	0.2
Carbon dioxide, free, mg/l	23
Dissolved oxygen, mg/l	0
Total solid, mg/l	290
Silica, mg/l	5
Total iron, mg/l	0.5-0.9
Calcium, mg/l	90
Magnesium, mg/l	3.5
Alkalinity (mg/l as CaCO ₃)	
Phenolphthalein	0
Methyl orange	210
Sulfate, mg/l	20
Chlorides, mg/l	20
Total hardness (mg/l as CaCO ₃)	240

much polyphosphate as iron was completely ineffective. Moreover, even when the amount added was equal to more than four times the quantity of iron no effect was obtained. At this level turbidity became apparent. Still higher dosages of polyphosphate gave some degree of protection of iron settlement, with increasing amount of turbidity appearing within a few hours. Besides, it was found that on a straight weight for weight basis, sodium silicate as SiO₂ was rather more effective than the polyphosphate and no turbidity was produced. In addition, it was found that a silica soil, activated sodium silicate, was approximately twice as effective as sodium silicate.

In the paper presented by GEORGE (1957) he mentioned that glassy phosphate would successfully stabilize dissolved iron and manganese. However, the glassy phosphate must be fed in proportion to the amount of iron and manganese in the water supply. He stated that under normal conditions a ratio of two parts of glassy phosphate for every part of iron and every part of manganese was required. If breakpoint chlorination was being practiced, or if the pH was 8.0 or higher a feed ratio of 4:1 should be used. A 4:1 ratio was also advisable during the first week or two of the treatment in those cases where the system contained an accumulation of old iron and manganese deposits.

DART and FOLEY (1970) reported that the addition of sodium silicate could be a simple and economic method of controlling marginally excessive iron content in many well water supply systems. Some of their studies are listed as follows:-

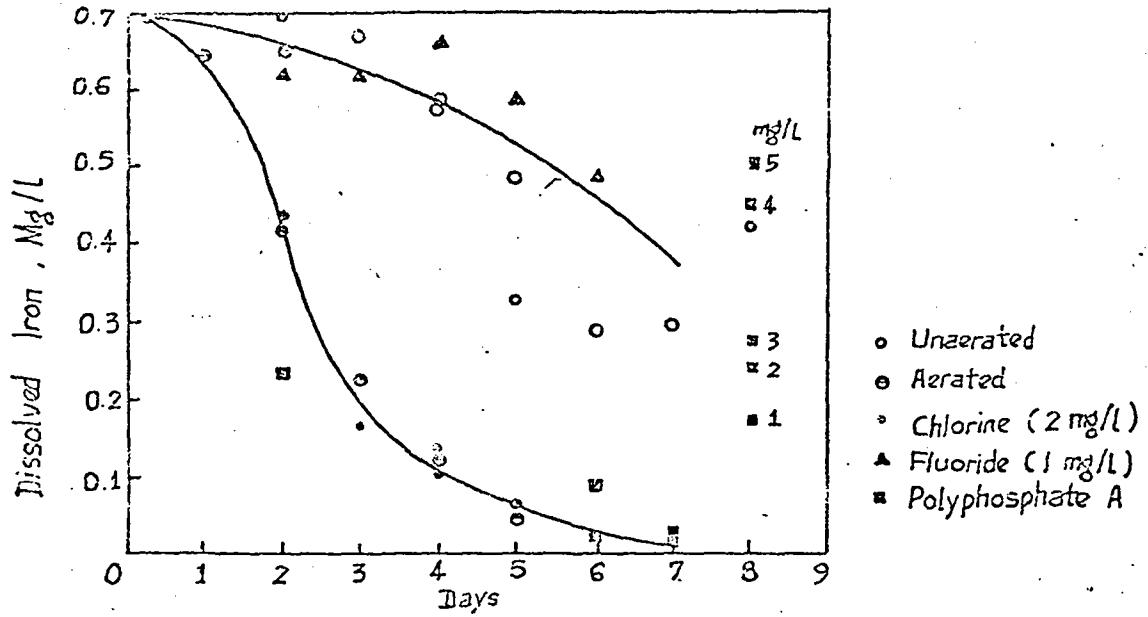


Fig. 2.2 — Effects of Single Treatment Only

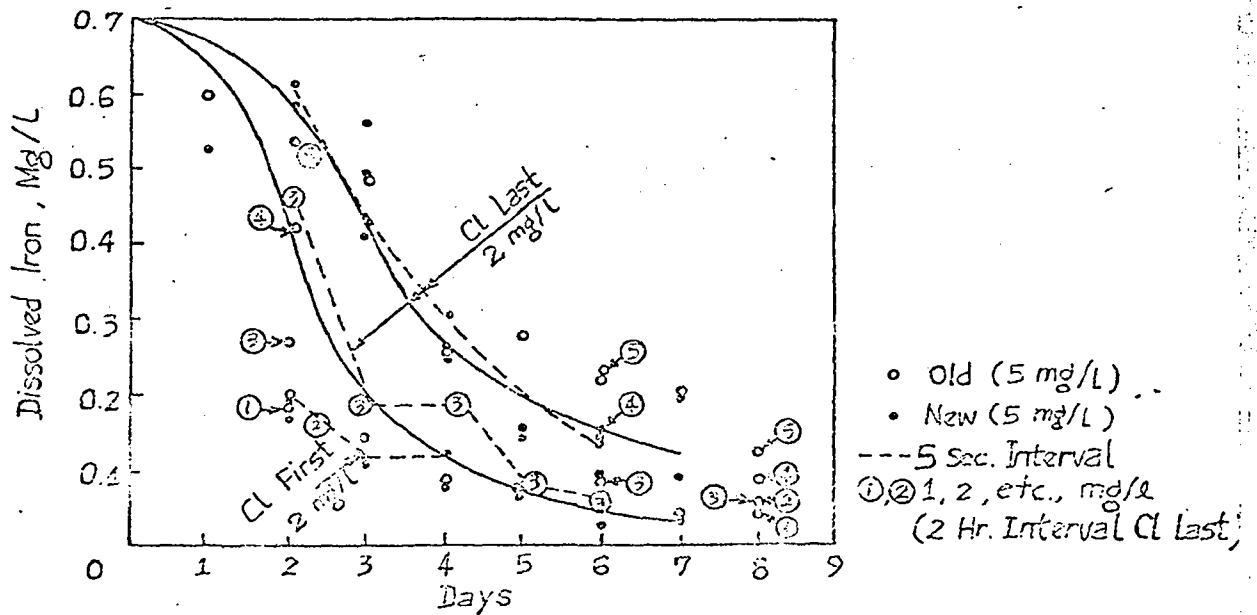


Fig. 2.3 — Polyphosphate-Chlorine

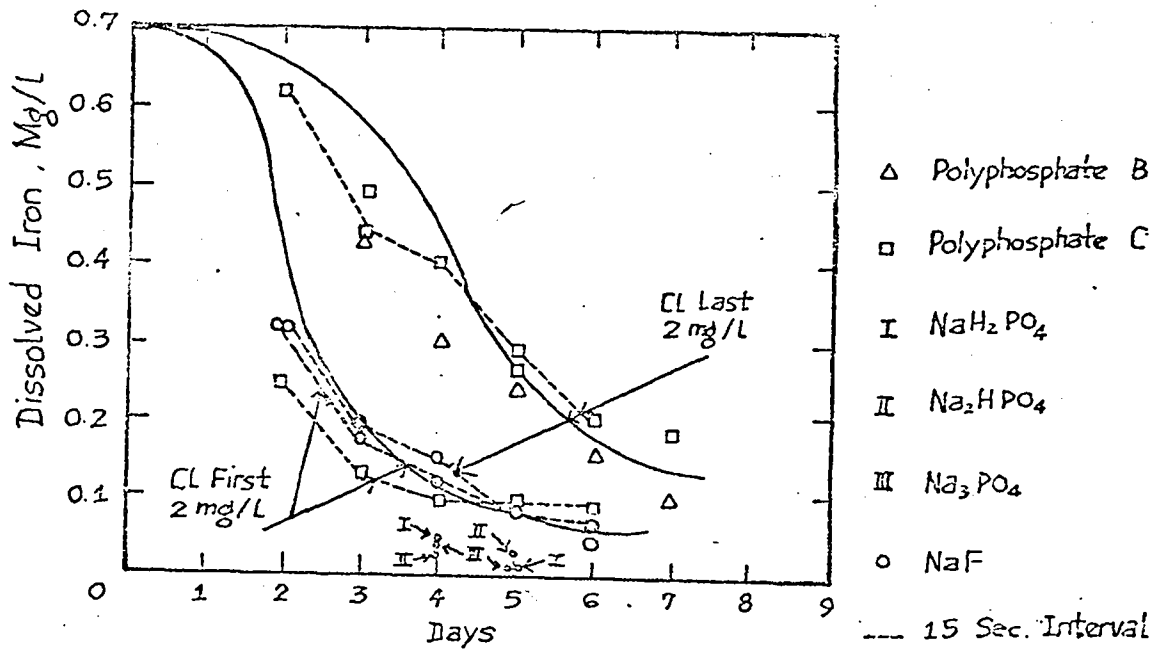


Fig. 2.4. — Phosphates, Polyphosphates and Fluoride

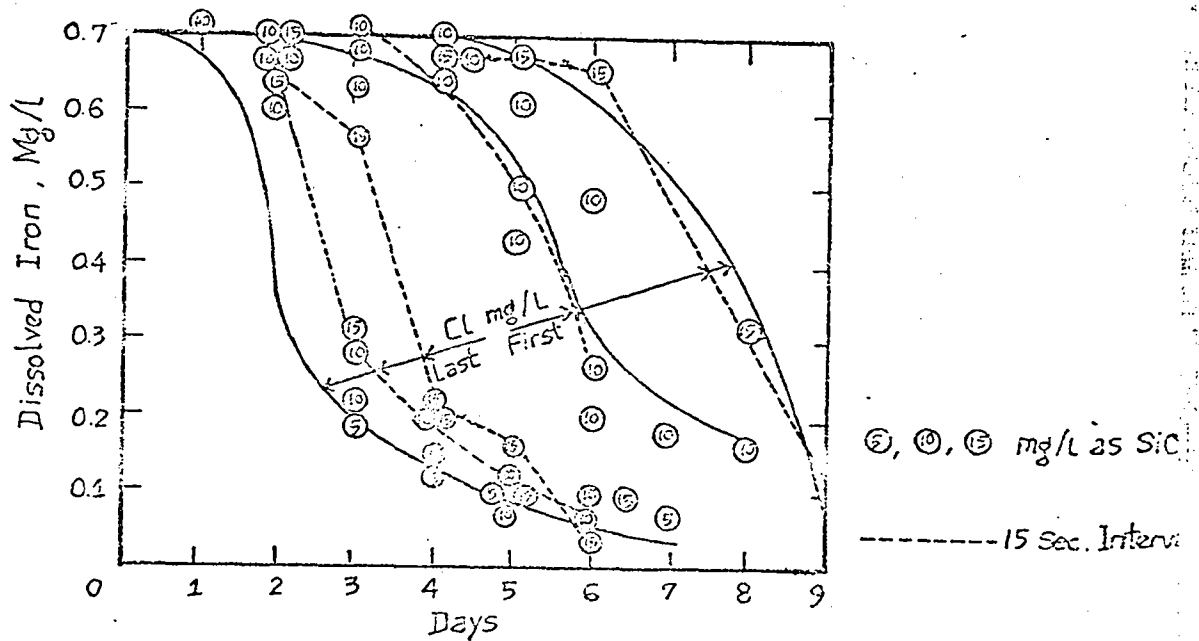


Fig. 2.5 — Sodium Silicate

- 1) Silicate stabilized iron better at higher pH. Waters with a resultant pH above 7.5 generally tended to be effectively treated.
- 2) Silicate-to-iron requirement were not linear. A minimum iron content may have required essentially no silicate.
- 3) Activated, partially neutralizes, or excessively prediluted silicate was not as effective as fresh, concentrated sodium silicate.
- 4) Optimum application of silicate always prove to be near simultaneous with chlorination and oxidation treatment. Addition of silicate much before or after iron oxidation yielded much lower efficiency. Lower efficiency commenced at about 15 seconds plus or minus from the time of oxidation.
- 5) Rapid mixing and cold water gave slightly improved stabilization reactions with silicate.

III EXPERIMENTAL INVESTIGATION

A. Design and Description of Equipment

The pilot plant was constructed according to the design of LIMRAT (1968). Wood and steel coated with anti-corrosion paints were used in order to avoid the contamination of iron from the apparatus and equipments used. The pilot plant was set up near the deep well pump at the bore hole, and consisted of the following units:-

- 1) Raw water constant head tank, pipe with controlled valves
- 2) Tray aerator
- 3) By-pass chamber
- 4) Mixing chamber
- 5) Chemical feeders
- 6) Upflow solids-contact precipitator

The schematic diagram of the pilot plant is shown in Fig. 3.1 whereas a detailed description of the components making up the pilot plant is included in Appendix.

B. Procedure and Analytical Methods

Samples of raw water, aerated water and finished water were collected and analysed. The following analyses were carried out to characterize the water at any stage of the treatment or study.

- 1) Total alkalinity
- 2) Free carbon dioxide
- 3) Dissolved oxygen
- 4) Total hardness
- 5) Total iron
- 6) Filtrable iron
- 7) pH
- 8) Temperature
- 9) Colour
- 10) Turbidity

Additional analyses for organic nitrogen, sulfates and COD were also performed to characterize the quantity of the raw water and free residual chlorine for finished water. Unless special stated, all the analyses were carried out according to the procedure given in STANDARD METHODS (1965). Table 3.1 gives a summary of the applied analytical methods.

Both total and filtrable iron were measured using spectrophotometer and colour by Nessler tubes.

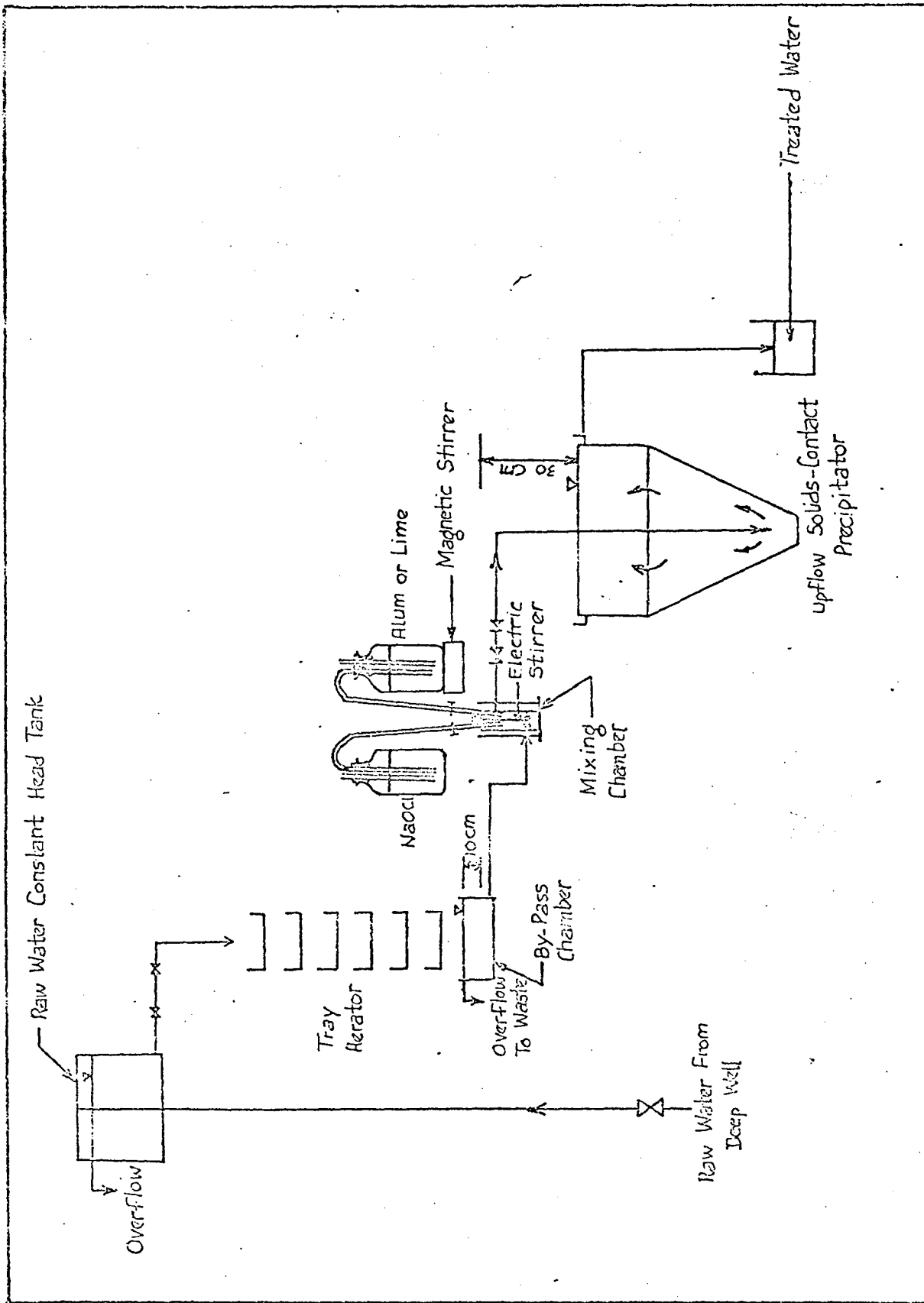


Fig. 3.1 — Schematic Flow Diagram of the Pilot Plant

Table 3.1 - Summary of Analytical Methods

Determination	Method Used	Standard Methods Page No.
Total Alkalinity	Titrimetric Method	54
Free Carbon Dioxide	Titrimetric Method	92
Dissolved Oxygen	Azide Modification Method	477
Total Hardness	EDTA Titrimetric Method	179
Filtrable Iron	Phenanthroline Method	189
Total Iron	Phenanthroline Method	189
Organic Nitrogen	Titrimetric Method	244
Sulfates	Turbidimetric Method	334
pH	Glass Electrode Method	276
Temperature	Mercury Thermometer	348
Colour	Nessler Tube	160
Turbidity	Turbidimeter	349
Free residual Cl ₂	DPD Titrimetric Method	129
COD	Titrimetric Method	495

C. Jar Tests

Groundwater from the bore hole was taken to perform jar tests in laboratory to determine optimum ranges of chlorine dosage, chlorine + lime dosage, chlorine + alum dosage for iron removal. The raw water was first analysed for pH, alkalinity, total hardness and total iron content.

In each set of jar tests, each of the six one litre beakers was filled with the raw water and placed in the stirring equipment which was set at a paddle speed of about 100 rpm. The respective chemical was then introduced and the solution was allowed to agitate rapidly for 30 seconds at this paddle speed of 100 rpm to ensure uniform distribution of the chemical throughout the body of water. The speed of the paddle was then slowed down to 30 rpm for 15 minutes flocculation time. After this period, the solutions were allowed to settle for an hour before the clear portion of the supernatant was taken for immediate analyses of pH, alkalinity and total iron. Both optimum pH and respective chemical dosages were studied and the obtained results used as a guide in operation of the pilot plant.

D. Operation of Pilot Plant

The constructed pilot plant consisted mainly of tray aerator and upflow solids-contact precipitator. The filtration unit was not installed because:

- 1) it would increase the capital cost of the treatment plant;
 - 2) it would require larger power consumption;
- and 3) the upflow solids-contact precipitator might do the job as well.

Groundwater at AIT campus was used as the water sample. From the results obtained by LIMRAT (1968), i.e., with the aerator dosing rates in the range 6.8-10.2 l/sec-m² (10-15 gpm/ft²) with coke ranging from 6.35-11.4 cm (2.5-4.5 in.) in size, as aerator medium yielded the best results in the oxidation and removal of iron of level 7-10 mg/l. Since the iron content of the AIT groundwater is different from this, the pilot plant did not adopt the determined aeration dosing rate. Hence, various aerator dosing rates, 5, 10, 15 l/sec-m², and 6-10 cm coke, and charcoal as medium were tried in order to obtain the optimum efficiency of the tray aerator in the iron removal.

Subsequently, experiments were carried out on the determination of the chemical dosage to develop the nucleus of the sludge blanket in the solids-contact precipitator. The chemicals tried were NaOCl, NaOCl + lime, and NaOCl + alum. Jar tests were performed in the laboratory before the actual run of the pilot plant and then the results obtained were used as a guide for the chemical dosage in the experiment with the pilot plant.

E. Determination of the Best Chemical for Prevention of the Settlement of Iron in the AIT Groundwater

In determining the best chemical additive for control of iron in the AIT groundwater, precautions were taken in sampling the water. Raw water (unaerated and unchlorinated) was introduced into 1 litre beakers by means of a tube reaching to the bottom of the 1 litre beakers. The beakers were filled cautiously from the bottom up to avoid aeration before the chemical was adequately mixed. A control containing no added chemical was also set up. Similar concentrations of each specific chemical were run simultaneously with the control. The solutions were set to stir slowly (at about 25 rpm) and visual observation made daily along with analyses for filtrable (reduced) iron. The samples were covered with paper to reduce evaporation and keep dust or dirt from entering the containers. The stirring and observation was continued until the last sample showed the breakdown of the system. The breakdown was indicated by the visual occurrence of reddish-brown flocs (the oxidation of iron to the insoluble state).

F. Determination of the Optimum Concentration of the Best Chemical to Produce the Desire Results

The experiment was repeated using various concentrations of the chemical considered to be the best and the same sampling precautions were followed. The lowest chemical concentration that gave a satisfactory retention of iron in suspension was chosen. No pH adjustment was made as it was stated by DART and FOLEY (1970) that water with pH above 7.5 usually tended to be effectively treated and the pH of AIT groundwater is often around 7.5. In addition, adjustment to higher pH than 7.5 might

give improvement, but had to take care of corrosion problem and also readjustment of pH might bring to practice.

No attempt was made to control temperature and aeration. This fact was taken into consideration; however, one of the features of this method was its simplicity. Since it could be performed using equipment usually available in the laboratory. Furthermore, in most distribution systems the temperatures maintained were less than room temperature with little or no aeration (except in the elevated tank).

IV PRESENTATION AND DISCUSSION OF RESULTS

A. Physical and Chemical Characteristics of AIT Groundwater

Raw water immediately pumped from the deep well pump at the bore hole was supplied to the pilot plant throughout the study. The analytical characteristics of the water are shown in Table 4.1 where it can be seen that the iron concentration was of the order of 0.25 mg/l.

Table 4.1 - Chemical Characteristics of Raw Water

	Data of Analysis			
	10-12-74	14-1-75	10-2-75	2-3-75
Total Alkalinity, as mg/l CaCO ₃	355	350	364	350
Total Hardness as CaCO ₃ , mg/l	102	100	108	106
pH	7.5	7.4	7.7	7.3
Temperature, °C	32	31	32	31
CO ₂ , mg/l	29.9	30	29	32
D.O., mg/l	1.2	1.3	1.2	1.2
Organic Nitrogen, mg/l	0.21	0	0	0
Sulfates, mg/l	22	23	-	-
Total iron, mg/l	0.17	0.28	0.31	0.31*
Filtrable iron, mg/l	0.15	0.24	0.30	0.26*
Colour (Nessler tube)	<5	<5	<5	<5
Turbidity, JTU	0.2	1.0	1.0	1.0
COD, mg/l	-	-	-	0*

* Composite Sample

Broadly speaking, there was slight variation of the water quality during the period of study. Grab samples were taken for the analyses at the early stage of study. However, it was thought later that the water characteristics might vary at different times of a day, and composite samples were then taken for iron analyses. It was found out too

that if the grab sample was taken in the early morning when the deep well pump first started to operate, higher contents of total iron, colour and turbidity were often expected. These higher values of total iron content, colour and turbidity might be due to the deep well pump stopping operation during the night time. Thus, at the beginning of the day when it first started to work, accumulated or contaminated iron from corrosion of the pipe line was flushed out. The total iron present in AIT groundwater was mainly in soluble ferrous form, thus before aeration and chlorination it was low in colour and turbidity measurements. Both total alkalinity and carbon dioxide content indicated that corrosion was likely to take place in the present water system. Lastly, the groundwater was low in hardness and organic content.

B. Investigation into the Efficiency of Aeration for Oxidation and Removal of Iron

Three types of packing media were used in the study; namely, lignite, charcoal, and coke. Lignite was found to be not applicable as the groundwater passed through it, it became soft and ultimately broke into small particles of size ranging from 1-2 cm. Oxidation and removal of iron by this medium was not good, thus the analytical results were not included here. In addition, it appeared that the raw water reacted with the packing medium and it gave additional colour to the aerated water. This colouration of water was not due to the oxidation of ferrous iron, as it was found that it bleached away as NaOCl was applied. Those analytical results which were obtained with charcoal and coke as aerator media are reported in Table 4.2 and 4.3, respectively.

(1) 6-10 cm Charcoal as Aerator Medium

Table 4.2 shows the characteristics of raw water and aerated water at the aerator dosing rates of 5, 10, and 15 l/sec-m² with charcoal 6-10 cm in size, as aerator medium. The stripping of carbon dioxide from the raw water after aeration led to the increase of total alkalinity as well as pH. But there was no significant change in total hardness. At all undertaken dosing rates, the designed aerator was capable of increasing the dissolved oxygen in the water after aeration to the lowest level of 7.4 mg/l and depressing the carbon dioxide to about 9 mg/l. From this analytical data, it showed such trend that increased aerator dosing rate lead to increased carbon dioxide remaining and decreased dissolved oxygen in the aerated water. These can be accounted by the fact that at lower aerator dosing rates the water was found to be more uniformly distributed and formed thin films and drops as it passed through the trays. This provided large surface area of the water in contact with the air and thus enhanced the chance for the carbon dioxide to leave the water and oxygen to enter into it.

The concentrations of total iron and filtrable iron in the raw water and aerated water at the first four hours of the operation of the tray aerator are listed in Table 4.2. - At any instant, the

Table 4.2 - Groundwater Characteristics before and after Passing Through the Aerator at 5, 10, 15 l/sec-m² with Charcoal 6-10 cm as Acrator Medium

Flow on Aerator l/sec-m ²		Analyses of Raw and Aerated Waters																			
		Temp. °C		pH		CO ₂ mg/l		T. Alkalinity mg/l as CaCO ₃		T. Hardness mg/l as CaCO ₃		D. Oxygen mg/l		Filtrable Iron, mg/l		Total Iron, mg/l					
		R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A		
5	0	31	-	7.5	-	32	-	360	-	100	-	3.0	-	0.220	-	0.250	-	-	-		
	1	31	28	7.6	8.4	32	9	364	380	108	105	3.1	7.6	0.220	0.200	0.250	0.230	0.230	8.0		
	2	31	28	7.5	8.3	31	9	362	380	107	104	3.0	7.6	0.230	0.210	0.250	0.230	0.230	8.0		
	4	31	28	7.5	8.3	31	8	360	385	107	103	3.1	7.6	0.220	0.200	0.240	0.220	0.220	8.3		
10	0	31	-	7.5	-	32	-	370	-	106	-	3.2	-	0.190	-	0.230	-	-	-		
	1	31	28	7.6	8.3	32	10	372	380	107	100	3.0	7.5	0.210	0.195	0.240	0.225	0.225	6.25		
	2	31	28	7.6	8.3	32	10	360	383	104	102	3.0	7.4	0.195	0.180	0.240	0.225	0.225	6.25		
	4	32	28	7.5	8.3	32	10	362	384	110	103	3.0	7.5	0.200	0.185	0.250	0.230	0.230	8.0		
15	0	31	-	7.6	-	32	-	360	-	108	-	3.0	-	0.210	-	0.250	-	-	-		
	1	31	28	7.6	8.3	32	11	368	380	106	100	3.1	7.4	0.210	0.200	0.240	0.230	0.230	4.20		
	2	31	28	7.6	8.4	32	11	358	380	106	102	3.0	7.4	0.200	0.190	0.240	0.230	0.230	4.20		
	4	31	28	7.6	8.4	31	10	358	378	104	102	3.0	7.4	0.200	0.190	0.240	0.230	0.230	4.20		

Table 4.3 - Groundwater Characteristics before and after Passing Through the Aerator at 5, 10, 15 l/sec-m² with Coke 6-10 cm as Aerator Medium

Flow on Aerator l/sec-m ²		Analyses of Raw and Aerated Waters																	
		Time of Operation Hr.	Temp. °C		pH		CO ₂ mg/l		T. Alkalinity as CaCO ₃ mg/l		T. Hardness as CaCO ₃ mg/l		D. Oxygen mg/l		Filtrable Iron, mg/l		Total Iron, mg/l		
			R	A	R	A	R	A	R	A	R	A	R	A	R	A	R	A	R
5	-	31	-	7.6	-	32	-	350	-	110	-	3.0	-	0.26	-	0.30	-	-	-
	0	31	28	7.5	8.5	32	1	348	396	110	106	3.0	7.8	0.26	0.23	0.30	0.26	13.3	
	1	31	28	7.5	8.4	32	1	350	390	110	102	3.2	7.8	0.25	0.22	0.30	0.24	20.0	
	2	31	28	7.4	8.4	32	0	350	390	108	107	3.0	7.4	0.25	0.22	0.30	0.24	20.0	
10	4	31	-	7.5	-	32	-	352	-	108	-	3.1	-	0.24	-	0.29	-	-	
	0	31	28	7.5	8.4	32	1	350	388	108	102	3.2	7.4	0.24	0.22	0.28	0.25	10.7	
	1	31	28	7.6	8.4	32	0	360	389	107	101	3.1	7.5	0.23	0.21	0.27	0.24	11.1	
	2	31	28	7.5	8.4	31	0	350	388	108	102	3.1	7.5	0.23	0.20	0.30	0.26	13.3	
15	4	31	-	7.5	-	32	-	352	-	108	-	3.1	-	0.24	-	0.28	-	-	
	0	31	28	7.5	8.3	32	0	348	390	110	107	2.9	7.3	0.24	0.22	0.28	0.26	7.7	
	1	31	28	7.5	8.3	32	1	354	388	110	106	2.9	7.3	0.24	0.22	0.26	0.24	7.7	
	2	31	28	7.5	8.3	32	1	352	392	110	102	2.9	7.4	0.24	0.22	0.27	0.25	8.0	

soluble ferrous iron was found to be at least 80% of the total iron content in the water. By aeration, a portion of the soluble ferrous iron was oxidized to the insoluble ferric form which might deposit on the surface of the charcoal medium. Both percentage of oxidation and percentage of removal of iron at the three aerator dosing rates are shown in Fig. 4.1 and 4.2, respectively. As the aerator dosing rate increased the percentage oxidation of iron decreased, that is, increasing the dosing rate from 5 l/sec-m² to 15 l/sec-m², decreased the percentage oxidation from 9.1% to 4.8%. One explanation might be due to the same phenomena as the increase of dissolved oxygen and decrease of carbon dioxide as dosing rate decreased. The same tendency was obtained for the percentage of iron removal. This was because more soluble ferrous iron was oxidized at lower dosing rates and thus greater amount of the insoluble ferric iron was precipitated out by deposition on the charcoal surface. Another reason was that at higher dosing rate, the water formed streamlines during passage through the aerator rather than fall dropwise with a longer detention time to trickle over the charcoal beds. Therefore, a higher percentage of iron removal was expected. The results showed that the best iron oxidation and iron removal were obtained at the aerator dosing rate of 5 l/sec-m², but even then only a small amount of iron was oxidized and removed in the charcoal tray aerator.

(2) 6-10 cm Coke as Aerator Medium

The trend of the raw water and aerated water characteristics when coke was used as aerator medium was the same as when 6-10 cm charcoal was used. However, much better results for carbon dioxide removal, iron oxidation and iron removal were obtained at all three aerator dosing rates. Table 4.3 and Fig. 4.3 and 4.4 show the analytical results. Again best results were obtained at the aerator dosing rate of 5 l/sec-m², but again iron oxidation and removal were relatively low.

(3) Comparison of the Aerator Performance between the Two Selected Aerator Media

Comparing Fig. 4.1-4.2 with those of Fig. 4.3-4.4, show that higher and better efficiency of the aerator was obtained when coke was used as the packing medium. However, best iron oxidation obtained was about 12%, and that of iron removal was about 20% at the aerator dosing rate of 5 l/sec-m². Apart from dissolved oxygen, carbon dioxide and iron content, there were no significant differences in total hardness, alkalinity, pH values in the aerated water after having pass through the two selected packing media. This implied that no chemical reaction had taken place between the packing media and the raw water. Thus, the differences in the efficiency of coke and charcoal for use as aerator media must be due to their surface characteristics.

The surface of coke is rugged and porous like fritted mass, whereas charcoal has a smoother surface. Doubtlessly, insoluble ferric iron could be more easily trapped by the rougher coke surface than on the charcoal surface. Consequently, higher removals of the total iron were expected.

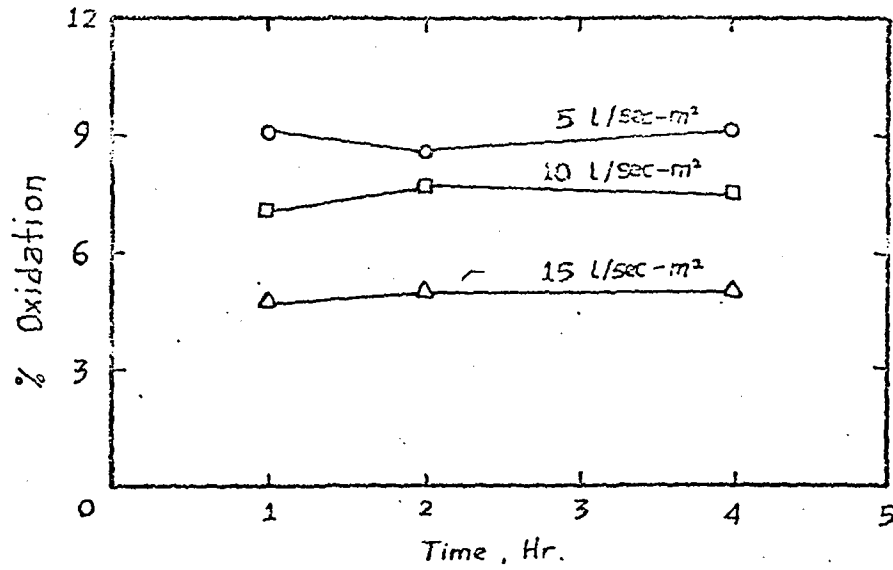


Fig. 4.1 — Iron Oxidation by Tray Aerator with 6-10 cm. Charcoal as Aerator Medium.

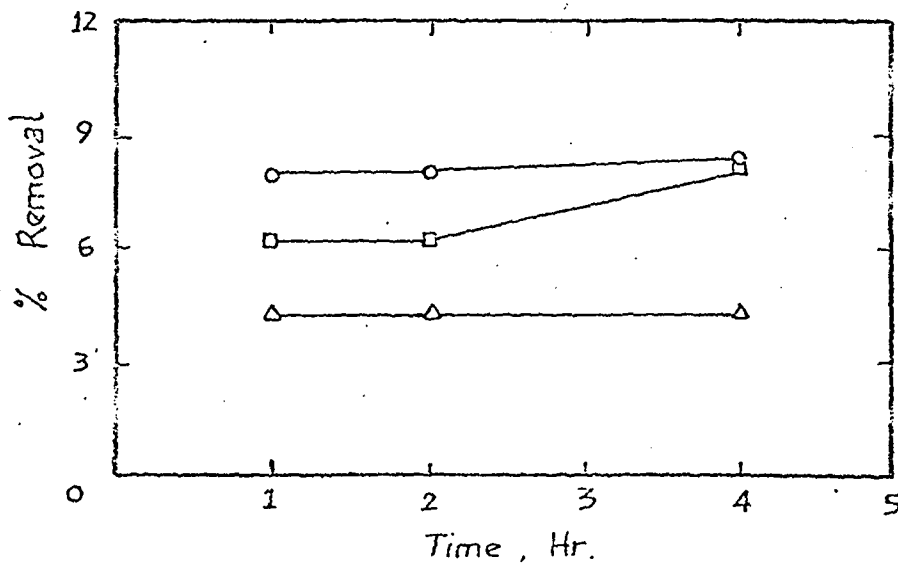


Fig. 4.2 — Iron Removal by Tray Aerator with 6-10 cm Charcoal as Aerator Medium.

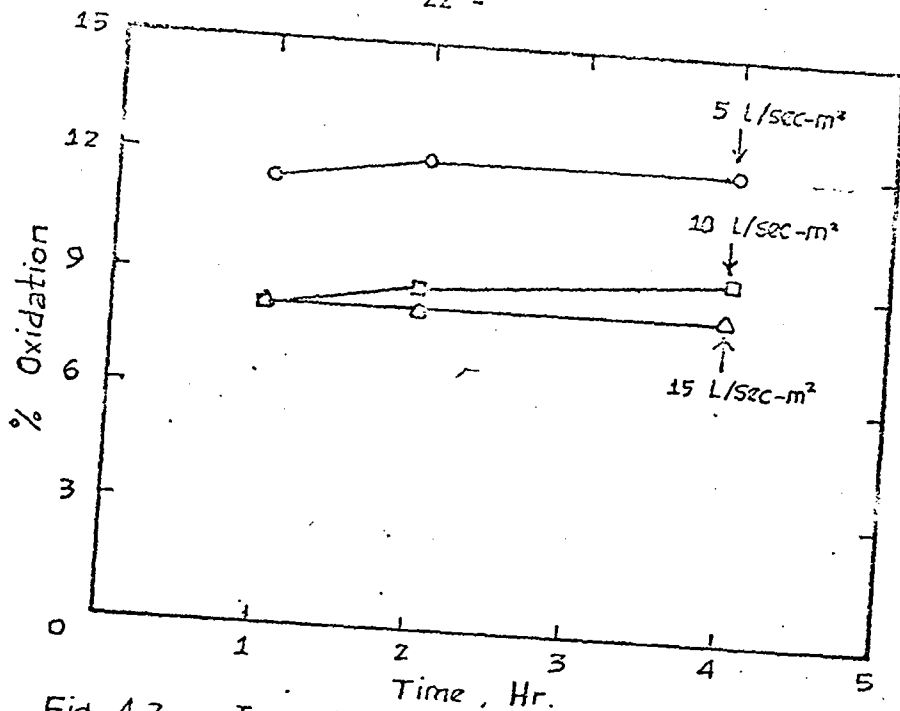


Fig. 4.3 — Iron Oxidation by Tray Aerator with 6-10 cm Coke as Aerator Medium.

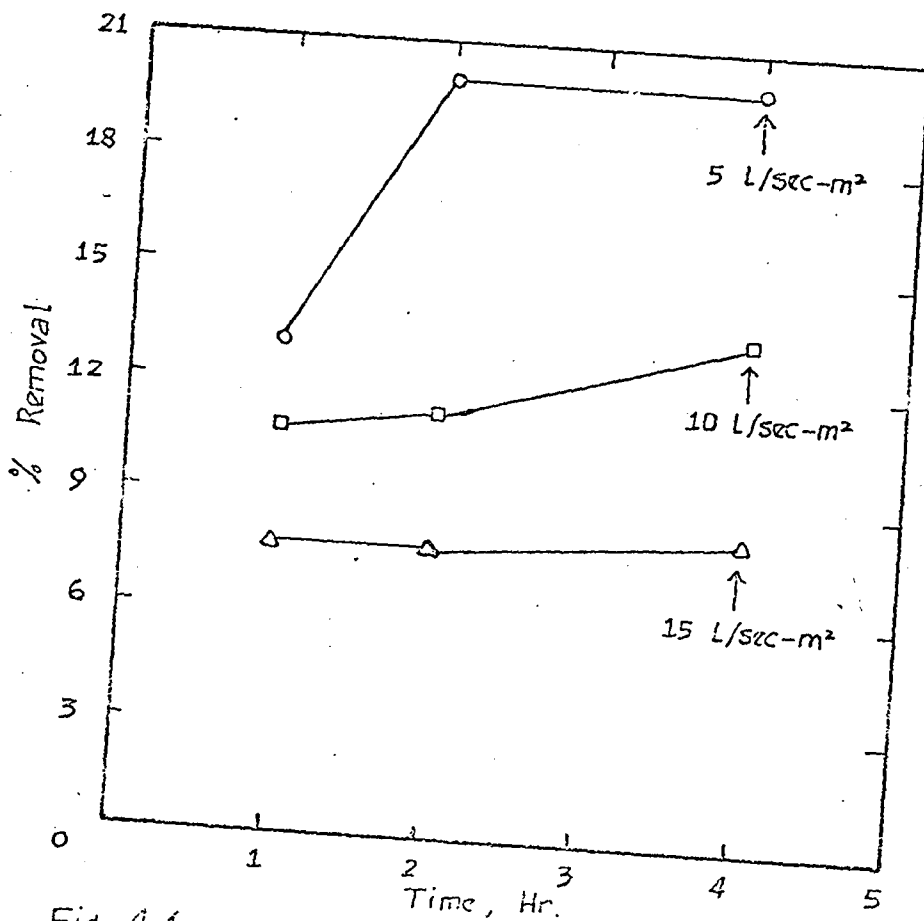


Fig. 4.4 — Iron Removal by Tray Aerator with 6-10 cm Coke as Aerator Medium.

C. Preliminary Investigations with Jar Tests

Selected combinations of oxidizing agent and coagulating agent were tested for their efficiency in removing iron. Table 4.4 shows the chlorine demand of AIT groundwater at 30 minutes contact time. The plot of residual chlorine versus applied chlorine dosage as shown in Fig. 4.5 indicates that there is no breakpoint of chlorine demand. However, by extrapolation, it is clear that more than 0.5 mg/l of applied chlorine will give a free residual chlorine.

The first set of jar test experiments was performed to determine the effective chlorine dosage that would give complete oxidation of iron which existed in the raw water, and also the corresponding iron removal after settling for an hour without disturbance. Table 4.5 shows the analytical results with an applied chlorine dosage of equal to or more than 8 mg/l, complete oxidation of iron could be achieved. However, the oxidized iron remained suspended in the water body for hours before coagulating to form large flocs which would settle readily. Accordingly, both lime and alum were selected and tested separately to see whether they could bring down these fine oxidized iron particles within a short period.

Table 4.4 - Chlorine Demand from AIT Groundwater (30 min. Contact Time)

Applied NaOCl Dosage as Free Cl. mg/l	Free Chlorine Residual mg/l
0.80	0.30
1.30	0.70
2.00	1.50
2.80	1.80
2.80	2.20
3.30	2.80
3.50	3.00
5.40	4.30

Table 4.5 - Iron Oxidation and Removal by Applied Chlorine

Applied HOCl as Cl	Filtrable Iron Before NaOCl, mg/l	Filtrable Iron After NaOCl mg/l	% Oxd.	Total Iron Before NaOCl mg/l	Total Iron After HOCl mg/l	% Rem.
0	0.22	0.22	0	0.24	0.24	0
1	0.22	0.15	31.8	0.24	0.24	0
2	0.22	0.06	72.7	0.24	0.24	0
3	0.22	0.06	72.7	0.24	0.24	0
4	0.22	0.06	72.7	0.24	0.24	0
5	0.22	0.05	77.3	0.24	0.24	0
6	0.23	0.05	78.3	0.24	0.24	0
7	0.23	0.04	82.6	0.24	0.24	0
8	0.23	0.00	100	0.24	0.23	4.1
9	0.23	0.00	100	0.24	0.93	4.1
10	0.23	0.00	100	0.24	0.24	0
11	0.23	0.00	100	0.24	0.24	0

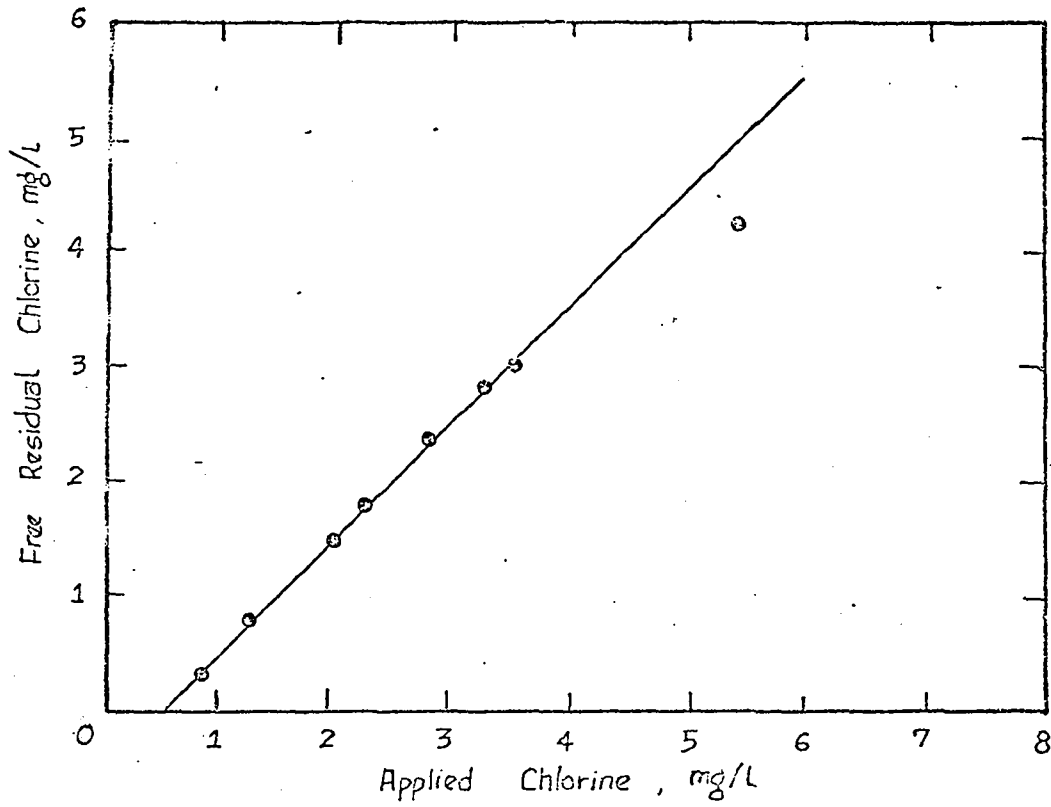


Fig. 4.5 — Chlorine Demand of AIT Groundwater
(30 minutes contact time.)

(1) Jar Test with NaOCl and Lime

Various concentrations of lime and 10 mg/l of NaOCl as free chlorine were applied in the jar test. 10 mg/l of NaOCl as free chlorine was selected instead of 8 mg/l, this was to ensue complete oxidation of soluble ferrous iron and also because the soluble ferrous iron content in the groundwater was often greater than 0.22 mg/l. The results of the jar tests are shown in Table 4.6. Obviously, increments in lime dosage above 150 mg/l would enhance the percentage of iron removal, but this would lead to high pH value in the finished water. This sounded very unattractive, as adjustment of pH of finished water would increase the cost of treatment. Thus 10 mg/l of NaOCl as free chlorine and 100 mg/l of lime was chosen as the effective dosages.

Accordingly, an experiment was carried out to investigate the effect of pH of the water on iron removal. That is, the dosage of 100 mg/l + 10 mg/l of NaOCl as free chlorine was applied at pH levels from 6 to 8.5 at 0.5 intervals. The results shown in Table 4.7 indicate that no significant improvement could be achieved and even worse results were obtained at pH values below 6. In conclusion, no pre-adjustment of pH was necessary if 100 mg/l lime + 10 mg/l NaOCl as free chlorine was used in the pilot plant study.

During these tests, supernatants in the jar tests had slight turbidity compared with the untreated water. However, the system was still applied to pilot plant study as it was believed that the upflow solids-contact precipitator with preformed sludge blanket might effectively trap the smaller flocs and give better removal than in the jar tests.

Table 4.6 - Chemical Analysis of AIT Groundwater During Jar Tests with Lime [Ca(OH)₂] as Coagulant

Jar Number	NaOCl as Cl ₂ mg/l	Lime mg/l	Floc Formation	pH	T. Alkalinity as CaCO ₃	T. Hardness as CaCO ₃ mg/l	* Free Residual Chlorine	** Residual Total Iron mg/l	% Rem
1	10	25	POOR	8.00	356	90	0.4	0.20	23.1
2	10	50	FAIR	8.05	360	80	0.4	0.13	50.0
3	10	75	FAIR	8.10	368	78	0.4	0.10	61.5
4	10	100	GOOD	8.40	380	60	0.4	0.08	69.2
5	10	125	GOOD	8.60	384	58	0.4	0.07	73.1
6	10	150	GOOD	8.80	395	56	0.4	0.06	76.9

* Contact time 4 hrs.

** Initial total iron = 0.26 mg/l

Table 4.7 - Effect of pH on Iron Removal by 100 mg/l Lime and 10 mg/l of NaOCl as Cl.

pH (initial)	6.0	6.5	7.0	7.5	8.0	8.5
NaOCl as Cl, mg/l	10	10	10	10	10	10
Lime, mg/l	100	100	100	100	100	100
pH (final)	8.2	8.4	8.65	8.90	8.95	8.0
Total Iron, mg/l	0.25	0.25	0.25	0.25	0.25	0.25
Residual Iron, mg/l	0.14	0.07	0.08	0.06	0.07	0.06
% Removal	44	72	68	76	72	76

(2) Jar Tests with NaOCl and Alum

Liquid alum at various concentrations, 10 to 120 mg/l and 10 mg/l NaOCl as free chlorine were applied in the jar tests. Table 4.8 shows the results. The best iron removal and good floc formation was at the dosage of 60-70 mg/l alum + 10 mg/l NaOCl as free chlorine. For greater efficiency, the optimum concentration of the chemicals as determined previously was subjected to raw water which had been adjusted to pH ranging from 6 to 8.5 at 0.5 intervals. The results are shown in Table 4.9, no significant improvement was obtained, but higher pH appeared to give a slightly better removal efficiency. However, from an economic viewpoint and corrosion and scale problem, no pH pre-adjustment was required. Hence, the dosage of 60 mg/l alum + 10 mg/l NaOCl as free chlorine was used in the pilot plant study.

Table 4.8 - Chemical Analysis of AIT Groundwater During Jar Tests with Alum as Coagulant

Jar No.	NaOCl as Cl mg/l	Alum mg/l	Floc Formation	pH	T. Alkali- nity as CaCO ₃ mg/l	T. Hardness as CaCO ₃ mg/l	*Free Residual Chlorine, mg/l	**Residual Iron mg/l	% Rem.
1	10	10	V. POOR	7.60	348	110	0.4	0.14	44
2	10	20	V. POOR	7.51	340	113	0.4	0.14	44
3	10	30	POOR	7.42	341	112	0.4	0.13	48
4	10	40	FAIR	7.41	338	112	0.4	0.12	52
5	10	50	FAIR	7.34	330	110	0.4	0.10	60
6	10	60	GOOD	7.31	325	107	0.4	0.10	60
1	10	70	GOOD	7.30	320	110	0.4	0.10	60
2	10	80	GOOD	7.29	320	108	0.4	0.12	52
3	10	90	GOOD	7.25	318	107	0.4	0.13	48
4	10	100	GOOD	7.20	315	106	0.4	0.13	48
5	10	110	V. GOOD	7.1	310	104	0.4	0.14	46
6	10	1120	V. GOOD	7.1	310	104	0.4	0.14	46

* Contact time = 4 hrs.

** Initial total iron = 0.25 mg/l.

Table 4.9 - Effect of pH on Iron Removal by 60 ppm Alum and 10 ppm NaOCl as Cl

Jar Number	1	2	3	4	5	6
pH (initial)	6.0	6.5	7.0	7.5	8.0	8.5
NaOCl as Cl, mg/l	10	10	10	10	10	10
Alum, mg/l	60	60	60	60	60	60
pH (final)	5.6	6.3	6.8	7.3	7.8	8.3
Total Iron, mg/l	0.25	0.25	0.25	0.25	0.25	0.25
Residual Iron, mg/l	0.20	0.16	0.14	0.11	0.10	0.09
% Removal	20	30	44	56	60	64

D. Investigations into the Efficiency of Pilot Plant Treatment with 100 mg/l Lime and 10 mg/l NaOCl as Free Chlorine - with Preformed Sludge Blanket

Operation of the pilot plant for a few hour hours was required to develop a sludge blanket of about 40 cm depth. It was then ready for the investigation of iron removal efficiency.

The conditions of operation of the pilot plant were as following:

1. Aerator dosing rate 5 l/sec-m²
2. Aerator medium 6-10 cm coke
3. Lime dosage 100 mg/l
4. NaOCl dosage (as free chlorine) 10 mg/l
5. Flow rate through the precipitator 1.9 l/min.
6. Detention time in the precipitator 3 hours

Table 4.10 shows the characteristics of the raw water, aerated water and finished water after treatment with 100 mg/l lime + 10 mg/l NaOCl as free chlorine.

The change in characteristics of aerated water was of the same trend as those shown in the evaluation of the coke tray aerator alone. By comparing the finished water with raw water, one distinct difference was that the finished water even though of much lower iron content on the one hand, its turbidity, which was due to the suspension of fine lime particles, increased greatly on the other hand. The very fine lime particles which were brought up to the clear water zone and finally passed over the weir of the upflow solids-contact precipitator went into the clear water tank. As aerated water, the finished water had very low carbon dioxide content and was rich in dissolved oxygen. When the minute amounts of suspended material in the finished water were removed by centrifugation, the finished water appeared to be as clear as the fresh water. The finished water contained 0.4 mg/l free residual chlorine. This was only implied

Table 4.10 - Physical and Chemical Characteristics of Raw(R), Aerated (A), and Finished (F) Waters after Treatment with 100 mg/l Lime + 10 mg/l NaOCl as Cl

Time, Hour	0			2			4			6			8			10			
	R	A	F	R	A	F	R	A	F	R	A	F	R	A	F	R	A	F	
Type of Water	31	-	-	31	28	28	32	28	28	31	28	28.5	31	28	28.5	31	28	28.5	F
Temperature, °C	7.4	-	-	7.4	8.3	8.6	7.5	8.3	8.6	7.4	8.3	8.6	7.4	8.3	8.6	7.4	8.35	8.6	F
pH	< 5	-	-	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	F
Colour	1	-	-	1	2	16	2	2	17	1	3	18	0	4	17	1	3	16	F
Turbidity	32	-	-	32	0	2	32	1	3	32	1	2	32	1	3	32	2	4	F
CO ₂ , mg/l	3.0	-	-	3.0	7.5	7.5	3.0	7.6	7.5	3.1	7.6	7.5	3.0	7.6	7.5	3.0	7.6	7.4	F
Dissolved Oxygen, mg/l	358	-	-	360	367	384	368	375	389	358	374	386	360	370	380	361	370	383	F
T. Alkalinity as CaCO ₃	108	-	-	108	107	70	107	110	65	108	108	60	108	110	67	107	106	62	F
T. Hardness as CaCO ₃	0.24	-	*	0.23	0.20	13.0	0.22	0.195	11.4	0.235	0.21	10.6	0.23	0.21	8.7	0.23	0.205	10.9	F
Filtrable Iron, mg/l	0.27	-	-	0.27	0.23	0.08	0.27	0.22	0.08	0.27	0.22	0.07	0.26	0.21	0.08	0.26	0.21	0.09	F
Total Iron, mg/l	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	F
% Removal by Aerator	-	-	-	14.8	-	-	18.5	-	-	18.5	-	-	19.2	-	-	19.2	-	-	F
% Total Removal	-	-	-	70.4	-	-	70.4	-	-	74.1	-	-	70.4	-	-	70.4	-	-	F

* Percentage of iron oxidation
 NOTE: The free residual chlorine of finished water = 0.4 mg/l

that the finished water would not cause colour problems upon chlorination, but also indicated that post chlorination was not necessary. In order to assure that the residual amount of iron, no matter in what forms, would not precipitate out throughout the period of distribution, the finished water was collected and re-chlorinated at the dosage of 2 mg/l NaOCl as free chlorine. A control of raw water was run parallel, both waters were under slow mixing of 25 rpm and 2 mg/l NaOCl as free chlorine was added after 24 hours. The control gave iron flocs after 24 hours while no iron precipitation was observed in the finished water for a continuous six days period. This process would overcome the accumulation of iron precipitate in the AIT water tower. The average percentage of total iron removal was around 70%, this percentage of iron removal could be achieved after the second hour of operation. A point that has to take care of is that very often the finished water ended up with turbidity as high as 18 JTU units which might need further treatment.

E. Investigations into Efficiency of the Pilot Plant Treatment with 60 mg/l Alum and 10 mg/l NaOCl as Free Chlorine - with Preformed Sludge Blanket

Due to the imperfect performance of the upflow solids-contact precipitator when lime + NaOCl were used for iron removal, an attempt was made to improve performance by changing lime to alum. Alum was selected as it was believed that the settling characteristics of the flocs would be better and as a result the relatively high turbidity of the finished water when lime + NaOCl were used would be overcome. Laboratory jar tests indicated that 60 mg/l alum + 10 mg/l NaOCl as free chlorine gave satisfactory result of iron removal. So, they were applied in the pilot plant study.

The conditions of the operation of the pilot plant were as following:

1. Aerator dosing rate	5	l/sec-m ²
2. Aerator medium	6-10	cm
3. Alum dosage	60	mg/l
4. NaOCl dosage (as free chlorine)	10	mg/l
5. Flow rate through the precipitator	1.9	l/min
6. Detention time in the precipitator	3	hours

Again, a preformed sludge blanket was developed beforehand. Table 4.11 shows the analytical results. The trend of change of temperature, colour, carbon dioxide, and dissolved oxygen were the same as when lime was applied, and could be accounted by the similar manner. The turbidity of the finished water was much lower than when lime was used and, in addition, better settling and trapping of the smaller flocs were observed. It was believed that the gelatinous characteristic of alum flocs made them more effective as a filtering medium.

The pH decreased in the finished water as a result of alum addition. Both total alkalinity and total hardness had no significant change.

Table 4.11 - Physical and Chemical Characteristics of Raw (R), Aerated (A) and Finished (F) Waters after Treatment with 60 mg/l Alum + 10 mg/l NaOCl as Cl

Time, Hour	0			2			4			6			8			10			
	R	A	F	R	A	F	R	A	F	R	A	F	R	A	F	R	A	F	
Types of Water																			
Temperature, °C	31	-	-	31	28	28.5	31	28	29	31	28	28.5	31	28	28.5	31	28	28.5	
pH	7.4	-	-	7.4	8.4	7.6	7.4	8.4	7.7	7.4	8.4	7.8	7.4	8.45	7.8	7.45	8.4	7.7	
Colour	< 5	-	-	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	
Turbidity	1	-	-	1	4	4	1	3	3	1	4	4	1	4	4	2	4	5	
CO ₂ , mg/l	32	-	-	32	0	4	32	0	5	32	0	3	32	0	3	32	0	2	
D.O., mg/l	3.0	-	-	3.0	7.6	7.5	3.0	7.4	7.5	3.0	7.5	7.5	3.0	7.6	7.5	3.0	7.6	7.5	
T. Alkalinity as CaCO ₃	355	-	-	354	368	326	356	370	330	360	374	333	355	370	334	335	371	330	
T. Hardness as CaCO ₃	109	-	-	110	108	108	110	107	110	108	106	109	106	105	108	106	104	110	
Free available Cl (3 Hrs)	-	-	-	-	-	0.38	-	-	0.38	-	-	0.37	-	-	0.4	-	-	0.38	
Filtrable Iron, mg/l	0.23	-	-	0.22	0.20	9.1*	0.21	0.19	9.5*	0.21	0.19	9.5*	0.22	0.19	13.6*	0.21	0.18	14.3*	
Total Iron, mg/l	0.25	-	-	0.24	0.215	0.09	0.25	0.21	0.11	0.25	0.21	0.10	0.24	0.20	0.09	0.24	0.20	0.09	
% Rem. by Aerator	-	-	-	-	14.9	-	-	16.0	-	-	16.0	-	-	16.7	-	-	16.7	-	
% Total Iron Removal	-	-	-	-	62.5	-	-	56	-	-	60	-	-	62.5	-	-	62.5	-	

* Percentage of Iron Oxidation by Aerator

Approximately 60% of total iron removal was achieved after the fourth hour of operation. Compared with the results obtained after lime addition, the percentage of removal was lower by 10%. The free residual chlorine of the finished water was found to be 0.38 mg/l, with colour measurement less than 5 units by Nessler tubes. To ensure that the residual amount of iron, approximately 0.1 mg/l, would not give colouration and iron sludge accumulation in the water tower, the finished water was collected and re-chlorinated by 2 mg/l NaOCl as free chlorine daily. A control of raw water was run simultaneously. Again, the control gave iron precipitation after 24 hours slow mixing, while no iron precipitation was observed for this finished water for as long as a period of 6 days. In other words, 60% removal of the present iron content in the groundwater could overcome both problems of colouration and accumulation of iron precipitation in the water supply and water tower respectively.

Fig. 4.6 shows the percentage of iron oxidation and removal with different applied chemicals, i.e., 100 mg/l lime + 10 mg/l NaOCl as free chlorine, and 60 mg/l alum + 10 mg/l NaOCl as free chlorine. From the graph, the percentage of iron oxidation and iron removal by the tray aerator in the two runs varied within a range, even though the operating conditions were maintained the same. A reason to account for this was the effect of wind. It was observed that some times the wind was so strong that it caused the water to spread out from the tray aerator. This might help in increasing the dissolved oxygen of the water, but it also lead some unaerated water passing to the by-pass chamber directly. The percentage of total iron removal was higher when lime + NaOCl was used instead of alum + NaOCl. However, the use of lime + NaOCl suffered from the disadvantage that the finished water often ended up with higher turbidity which might need further treatment, for example, sand filtration. Treatment of alum + NaOCl, no doubt gave lower percentage of total iron removal, approximately 10% lower; but the quality of the finished water was acceptable. Under optimum conditions, further treatment seemed to be unnecessary.

The stability of the treatment system depends mainly on the performance of the coke tray aerator and the upflow solids-contact precipitator. From the work by LIMRAT (1968), he reported that during his three months study using coke tray aerator which was capable to remove about 1 mg/l of iron initially started to decrease its efficiency at the end of the study. Thus, it is predicted that for this water treatment system the coke may have to be replaced after putting into operation for two to three years as the iron content in the AIT groundwater is much lower compared with that undertaken by LIMRAT (1968). That is because the deposited iron filled up the pores of the coke surface. This estimation is only valid if the iron level maintains at the present concentration. The stability of the upflow solids-contact precipitator depends on the sludge blanket, the effect of chemical mixing, and the detention time in the upflow solids-contact precipitator.

The yearly expenses on the chemicals for this treatment system are summarized in Table 4.12. The cost estimation is based on the present average water production, 455,000 l/day (100,000 gal/day).

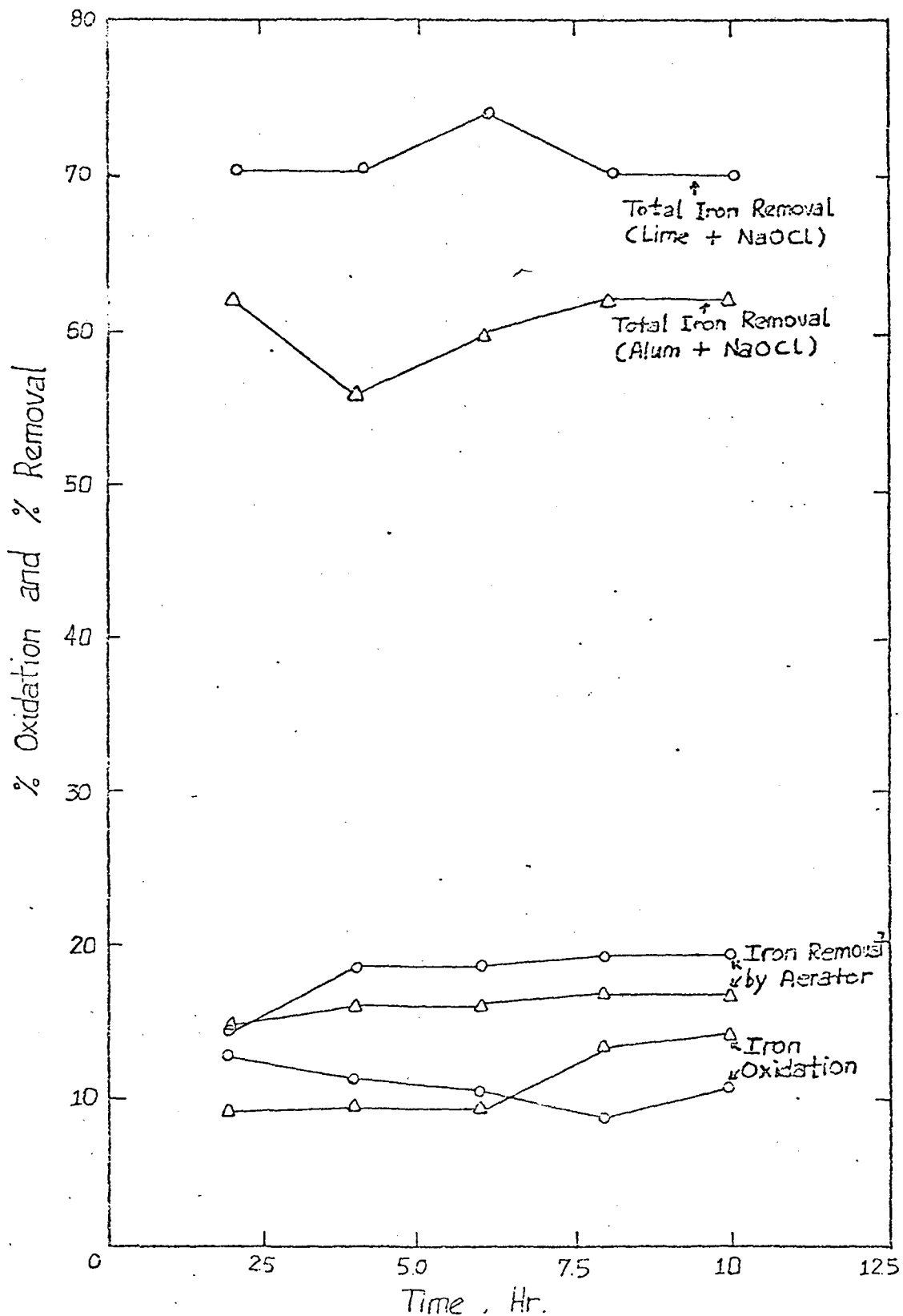


Fig. 4.6 — Iron Oxidation and Iron Removal with 100 mg/L Lime + 10 mg/L NaOCl as Chlorine and 60 mg/L Alum + 10 mg/L NaOCl as Chlorine.

Table 4.12 - Yearly Expenses on Chemicals

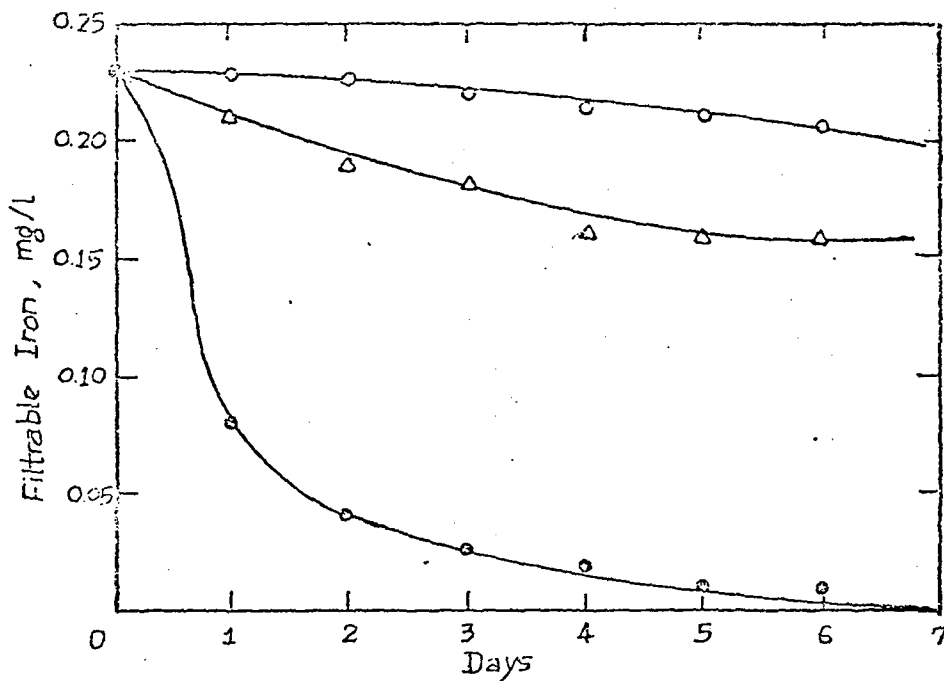
Item	Unit	Unit Price, Baht	Quantity	Coke Tray Aerator Iron Removing Plant with Lime + NaOCl Addition, Baht	Coke Tray Aerator Iron Removing Plant with Alum + NaOCl Addition, Baht
Coke	m ³	1,000	24	8,000	8,000
Lime	Kg	5.0	15,000	75,000	-
Alum	Kg	5.75	9,000	-	51,750
NaOCl	Kg	3.25	60,000	195,000	195,000
Total				278,000	254,750

Additional operating cost such as power consumption for heads and mixing, labours, transportation, sludge disposal, and maintenance should be included in this treatment system.

F. Determination of the Best Chemical for Prevention of the Settlement of Iron in AIT Groundwater

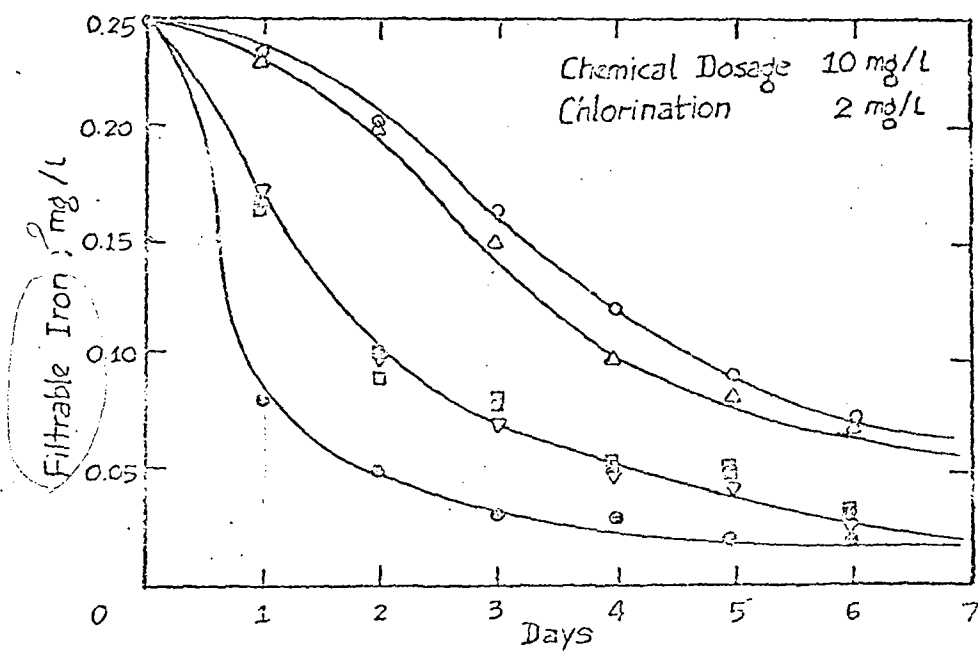
Before the best chemical for the prevention of iron settlement in AIT groundwater was determined, the effect of the groundwater towards chlorination was studied. Results are shown in Fig. 4.7. It was found that the soluble ferrous iron content in the untreated water was rather stable, after a period of six days, less than 10% of the initially present soluble ferrous iron was oxidized to the insoluble ferric iron and gave no coloration problem. It was found too that if the applied chlorine dosage was controlled at 1 mg/l, no colour problems were encountered, but slight iron precipitation occurred on the fourth day. However, at the applied chlorine dosage of 2 mg/l, iron precipitation appeared after 24 hours. Accordingly, an attempt was made to look into some selected chemicals to overcome the colouration problem.

Sodium silicate, sodium phosphate, sodium polyphosphate, disodium phosphate, and trisodium phosphate were selected and subjected to test. Laboratory results are shown in Fig. 4.8. This set of results was obtained at a chlorine dosage of 2 mg/l and 10 mg/l of the respective chemical. The control, i.e. only raw water + 2 mg/l chlorine, gave relatively large amounts of iron precipitate on the first day and this increased gradually but not significantly as time went on. The apparent colour of the control water exceeded 5 units by Nessler tube in the first few hours, but reduced greatly after 24 hours. The increase in colour was due to the suspended ferric iron. It was believed that the soluble ferrous iron once oxidized by applied chlorine to form the insoluble ferric state, might be considered as an unstable monomer with an immediate tendency to polymerize into large molecular structures. These large molecular structures joined to form visible iron flocs and finally



- Untreated Ground Water
- △ Chlorinated (1 mg/l)
- Chlorinated (2 mg/l)

Fig. 4.7 — Effect of Chlorination



- Polyphosphate
- △ Silicate
- NaH₂PO₄
- ▣ Na₂HPO₄
- ▽ Na₃PO₄
- Chlorinated (2 mg/l)

Fig. 4.8 — Effect of Various Selected Chemicals

these flocs grew very large in size and settled to the bottom of the container. Colour was greatly reduced again once these very large flocs were formed. Sodium, disodium, and trisodium phosphates appeared to be ineffective, they all allowed some iron precipitation on the first day and this increased to a great extent from the second day onwards. However, both sodium polyphosphate and sodium silicate seemed to be applicable, they only started to give iron precipitation on the second day and this increased slowly as time proceeded. Thus, it was believed that a higher dosage of these chemicals might withhold the iron satisfactorily in solution with no colouration.

Fig. 4.9, 4.10 and 4.11 show the effect of higher dosages of sodium polyphosphate and sodium silicate in controlling the suspended iron from precipitation. With regard to the 15 mg/l dosage, not much improvement was achieved compared with the previous work, and iron started to precipitate out after 1.5 day. The 20 mg/l dosage test showed that iron precipitation started on the third day. Much higher dosages were then tried, when a dosage of 30 mg/l of the selected chemicals was tried, it appeared to tie up the iron to the fourth day, while further increase in chemical dosage did not delay the iron precipitation greatly.

Hence, from economic viewpoint, if AIT is going to adopt this method for control of its iron problem, 30 mg/l of either silicate or polyphosphate can be applied. The obtained results showed that much more chemical dosage was required than those reported in literature. The yearly expenses on the chemicals are shown in the below Table 4.13.

Table 4.13 - Yearly Expenses on Chemicals by Iron Withholding Method

Item	Unit	Unit Price Baht	Quantity	Chemical Expenses Baht
NaOCl	Kg	3.25	12,000	39,000
Sodium silicate or polyphosphate	Kg	100	4,500	450,000
Total				489,000

From the above figure, the operating cost is rather expensive; in the long run, this might not be economic.

The results of this study indicate that the two treatment systems described could overcome the iron problem but would both prove to be rather expensive. Perhaps a more practicable alternative would be modification of the present system by installing a pressure filter, either of sand or diatomaceous earth on the outlet side of water tower. Chlorination, as now applied, will serve for iron oxidation, the water tower will serve as a sedimentation tank and the pressure filter will act as a polisher without breaking the head on the distribution system. However,

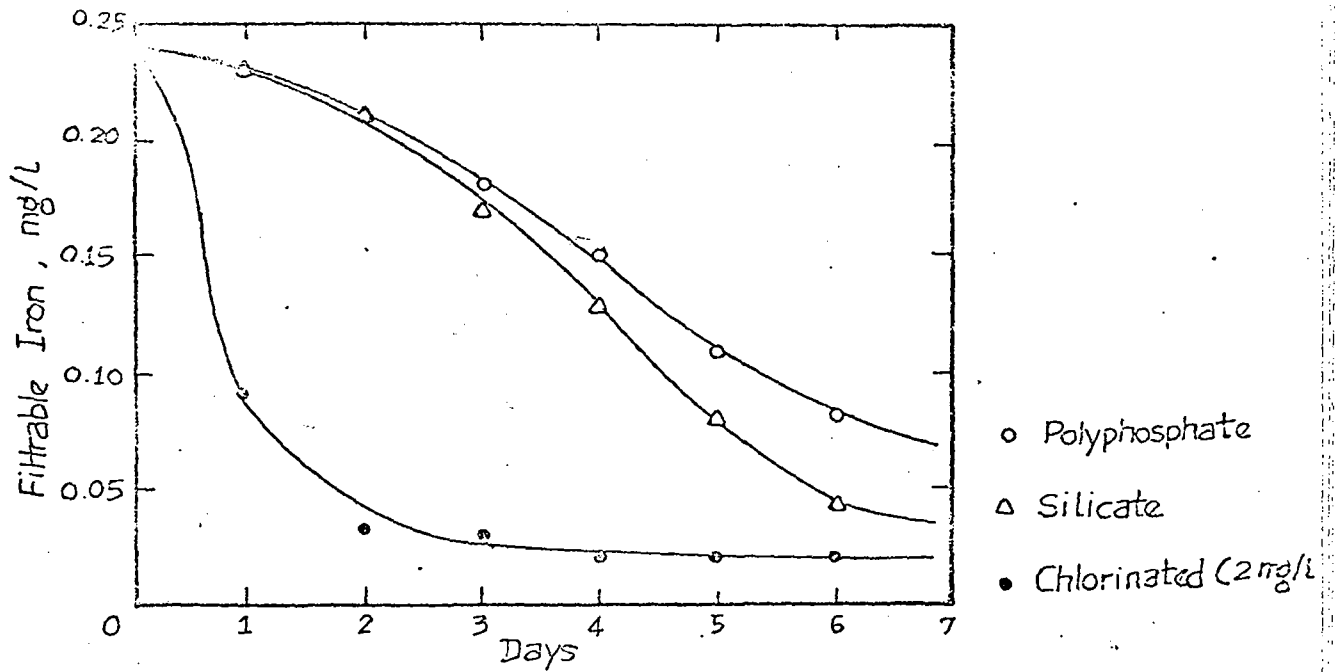


Fig. 4.9 — Effect of 15 mg/L of Polyphosphate and Silicate.

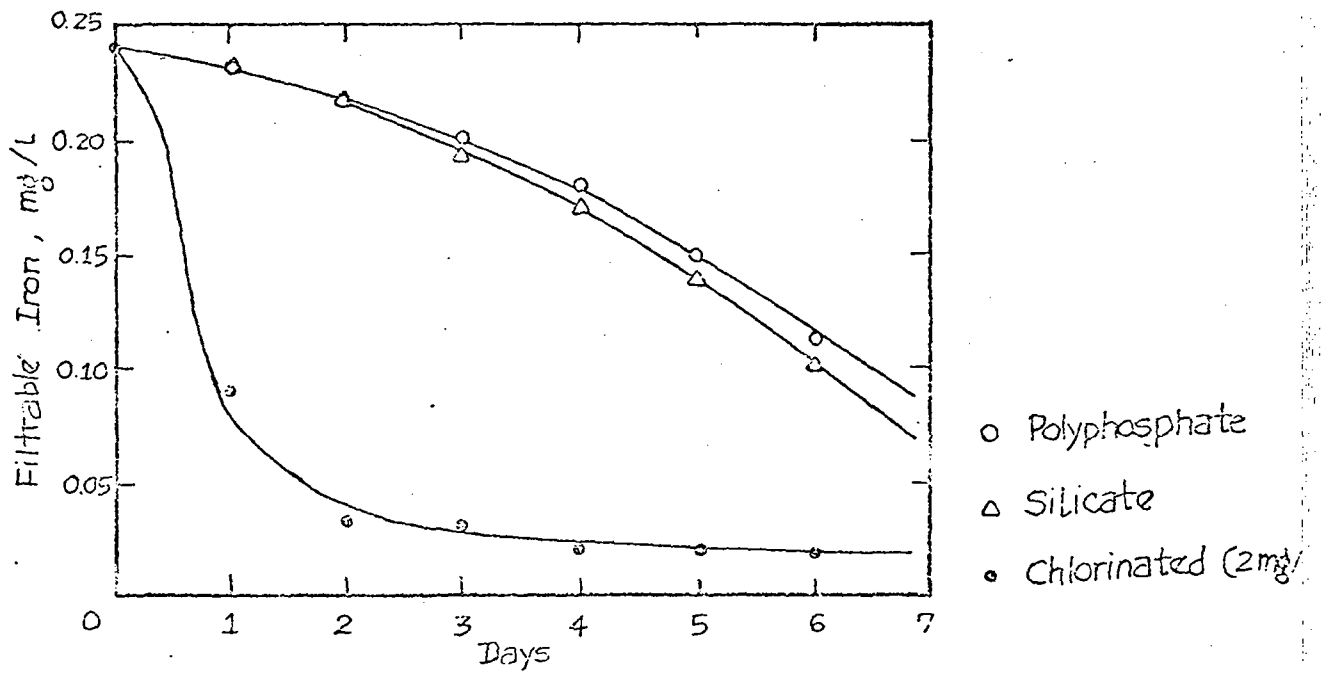


Fig. 4.10 — Effect of 20 mg/L of Polyphosphate and Silicate.

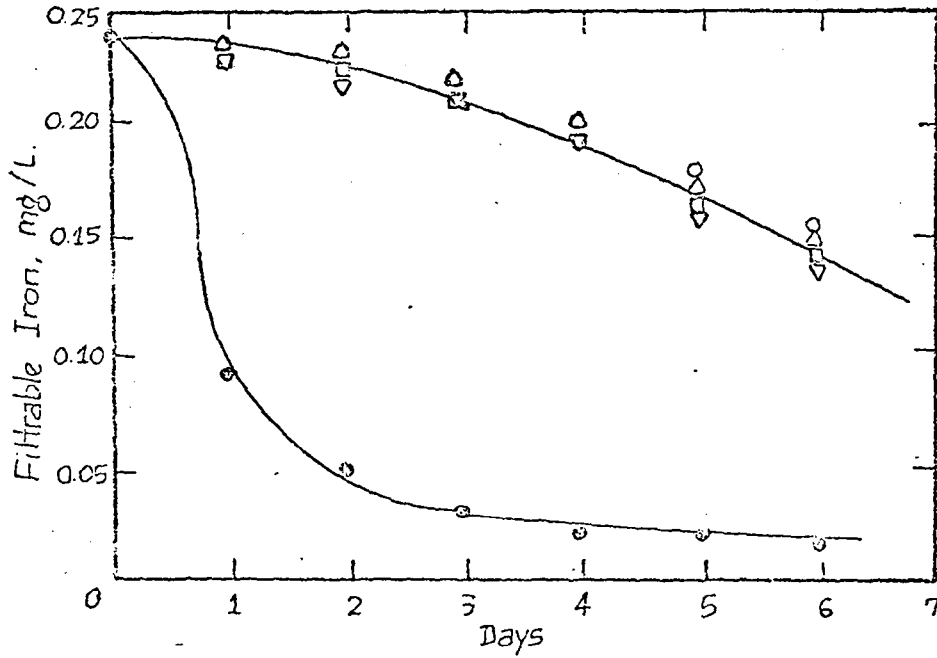


Fig. 4.11 — Effect of 30 mg/L and 40 mg/L Silicate and Polyphosphate:

- Chlorinated (2 mg/L)
- Polyphosphate (30 mg/L)
- △ Silicate (30 mg/L)
- Silicate (40 mg/L)
- ◇ Polyphosphate (40 mg/L)

a study of the penetration of iron floc into the pressure filter bed must be made to arrive at a design filtration rate. The overhead water tower should be equipped with a sludge draw-off pipe so that de-sludging can be accomplished without closing down the system.

V CONCLUSION

During this part of work, the following conclusions have been arrived at:

1. From the study, it was found that if the applied chlorine dosage could be controlled to the highest amount of 1 mg/l, this would prevent both colouration and iron sludge accumulation problems in the AIT groundwater supply, provided the level of iron concentration is of the present order 0.25 mg/l.

2. The coke tray aerator was found to be more efficient than the charcoal aerator in oxidation and removal of iron, as well as in carbon dioxide removal. Aeration was not necessary for iron removal alone because chlorination would more effectively oxidize the iron. As corrosion would be caused by an excess of carbon dioxide, the aeration unit might be desired.

3. At optimum conditions, the percentage of iron oxidation and iron removal by the coke tray aerator were about 12% and 20%, respectively.

4. Iron oxidation and removal could be effected by free residual chlorination at normal pH values and without elaborate treatment.

5. In the pilot plant operation, the upflow solids-contact precipitator with preformed sludge blanket, 100 mg/l lime + 10 mg/l NaOCl as free chlorine, and 3 hours detention time could achieve total iron removal up to 70%, so that the remainder would not cause colour problem. However, the turbidity of the finished water increased up to 18 JTU units, this is about the WHO Standard which set the limit for drinking water not more than 5 JTU units. The turbidity was due to the very fine lime particles which overflowed to the clear water tank. Hence, further treatment might be necessary, for example, sand filtration.

6. In pilot plant operation, when 100 mg/l lime was replaced by 60 mg/l alum, approximately 60% of total iron removal was obtained. With this percentage of removal, it was enough to give the finished water with no colour problem upon chlorination & no iron precipitate.

7. Post chlorination was not necessary if 10 mg/l NaOCl as free chlorine was applied at the initial stage of treatment for iron removal.

8. The stability of this treatment system depends mainly on the performance of the coke tray aerator and the upflow solids-contact precipitator. It is predicted that the coke may have to be replaced after the aerator is operated for 2 or 3 years. The stability of the upflow solids-contact precipitator depends on the sludge blanket, the

effect of chemical mixing, and detention time.

9. Results of a laboratory study of the effects of various agents on the rate of iron settlement in chlorinated groundwater are presented. Mono-, di-, and tri-sodium phosphate failed to withhold the iron in the water, and precipitation started to occur in 1.5 days.

10. Dosages of both sodium silicate and polyphosphate at 30 mg/l gave some protection and delayed iron precipitation for up to four days. As the chemical dosage was increased to 30 mg/l, sodium silicate seemed to tie up the iron better than polyphosphate. A chemical dosage higher than 40 mg/l gave no significant improvement in prevention of iron settlement.

11. As far as chemical consumption is concerned, the yearly expenses on chemicals of the iron withholding method is about 2 times the cost of iron removal by the coke tray aerator and chemical precipitation. Thus, in the long run, the former might not be economic.

12. The results of this study indicate that the two treatment systems described could overcome the iron problem but would both prove to be rather expensive. Perhaps a more practicable alternative would be modification of the present system by installing a pressure filter either of sand and diatomaceous earth on the outlet side of the water tower. Chlorination, as now applied, will serve for iron oxidation, the water tower will serve as a sedimentation tank and the pressure filter will act as a polisher without breaking the head on the distribution system. However, a study of the penetration of iron floc into the pressure filter bed must be made to arrive at a design filtration rate.

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APPENDIX

Description of Equipment

1. Raw Water Constant Head Tank

The tank acted as a raw water reservoir, it was made of steel sheet coated inside with anti-corrosion paint. The dimensions of the tank were 90 cm in length, 60 cm in width and 75 cm in height. The total volume of the tank was 405 litres. At the middle of the shorter side of the tank and 15 cm from the top an overflow cast iron pipe 5 cm inside diameter was connected. During operation, the surface of the water in the tank was kept at about the upper rim of the overflow hole, making the actual volume of water in the tank during operation to be $90 \times 60 \times 60 \text{ cm}^3 = 324$ liters all the time. An outlet made of cast iron pipe, 5 cm internal diameter was located at the bottom of the opposite side. The outlet pipe had 2 control valves as shown in Fig. 1.

2. Tray Aerator

The aerator was made of wood was a multiple tray type 30 cm square and approximately 1.8 m high. It consisted of six slat bottom trays spaced at 30 cm apart. The tray bottom formed by arranging 1 cm x 2.5 cm wood slats 1 cm apart coke and charcoal media in the study. The design drawing of the aerator was shown in Fig. 2.

3. By-pass Chamber

An open chamber with dimensions of 45 cm in length, 32 cm in width and 22.5 cm in height was made of steel sheet. At the lower end of one of the shorter sides of the chamber, an outlet cast iron pipe 1.25 cm internal diameter with a control valve. The chamber was placed under the aerator to collect aerated water and discharged it through the outlet tube to the mixing chamber. Fig. 3 shows the details of the chamber.

4. Chlorination and Chemical Mixing Chamber

The 1.96 litre circular mixing chamber was made of steel tube with an inside diameter 10 cm and height of 25 cm. It was placed at the centre of a 17.5 cm circular box and 25 cm high. The aerated water flew by gravity from the by-pass chamber into the mixing chamber through an inlet cast iron pipe of 1.25 cm internal diameter. An outlet cast iron tube of 1.875 cm internal diameter was connected to the mixing chamber on the opposite side to the inlet tube. Mixing chamber on the opposite side to the inlet tube. Both NaOCl and chemical were fed into the mixing chamber by allowing them to flow from two 10 - 1 bottles by gravity. An electric stirrer was used to mix the chemicals with the incoming water.

The flow rate to the upflow solid contact precipitator was controlled by a control valve installed at the outlet of the mixing chamber. Fig. 4 shows the detailed drawing of the mixing chamber and the outlet tube.

5. Upflow Solids-Contact Precipitator

The precipitator was made of steel sheet 0.4 cm thick and was of 75 cm long and 30 cm high on the upper square zone. The lower pyramidal zone or slurry pool was 62.5 cm deep with a wall slope of 2 vertical to 1 horizontal thus making a total height of 92.5 cm. The bottom of the pyramidal section was 12.5 cm square and connected with a 5 cm internal diameter drained pipe. At one side of the sloping walls, a transparent window, 10 cm by 42.5 cm was constructed with 2.5 cm thick perspex plate for observing the formation of the sludge blanket in the slurry pool. The precipitator was coated with anti-corrosion paint.

The dosed water was introduced into the bottom of the upflow solids contact zone by means of a central down draught cast iron pipe 1.875 cm internal diameter. It was then allowed to flow upwards through the slurry pool into a clear water zone, and decant over the outlet weir into the outlet trough. At the bottom of the outlet trough, near one corner was a clear water outlet tube for discharging treated water into clear water storage.

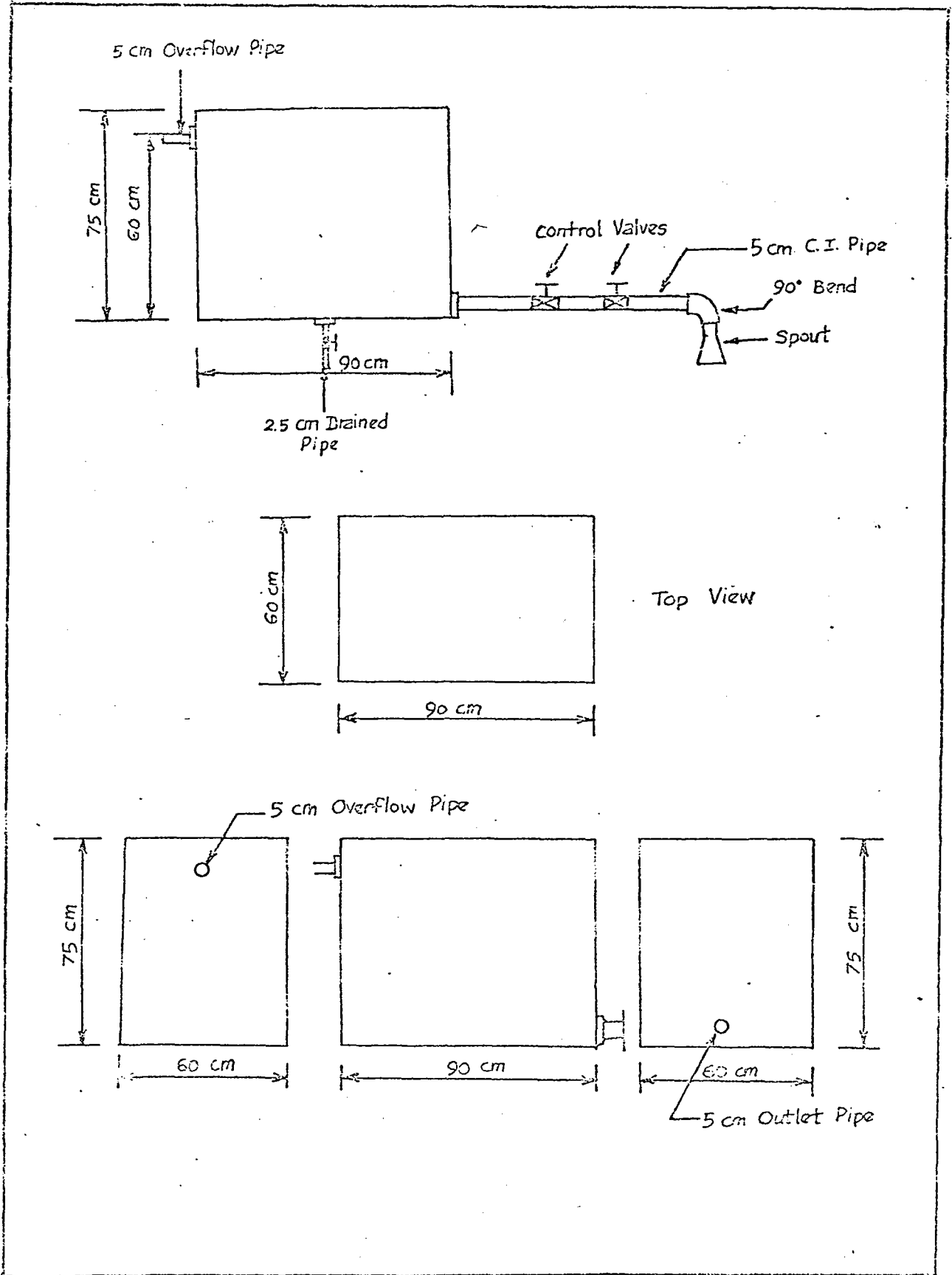


Fig. 1 — Details of Raw Water Constant Head Tank.

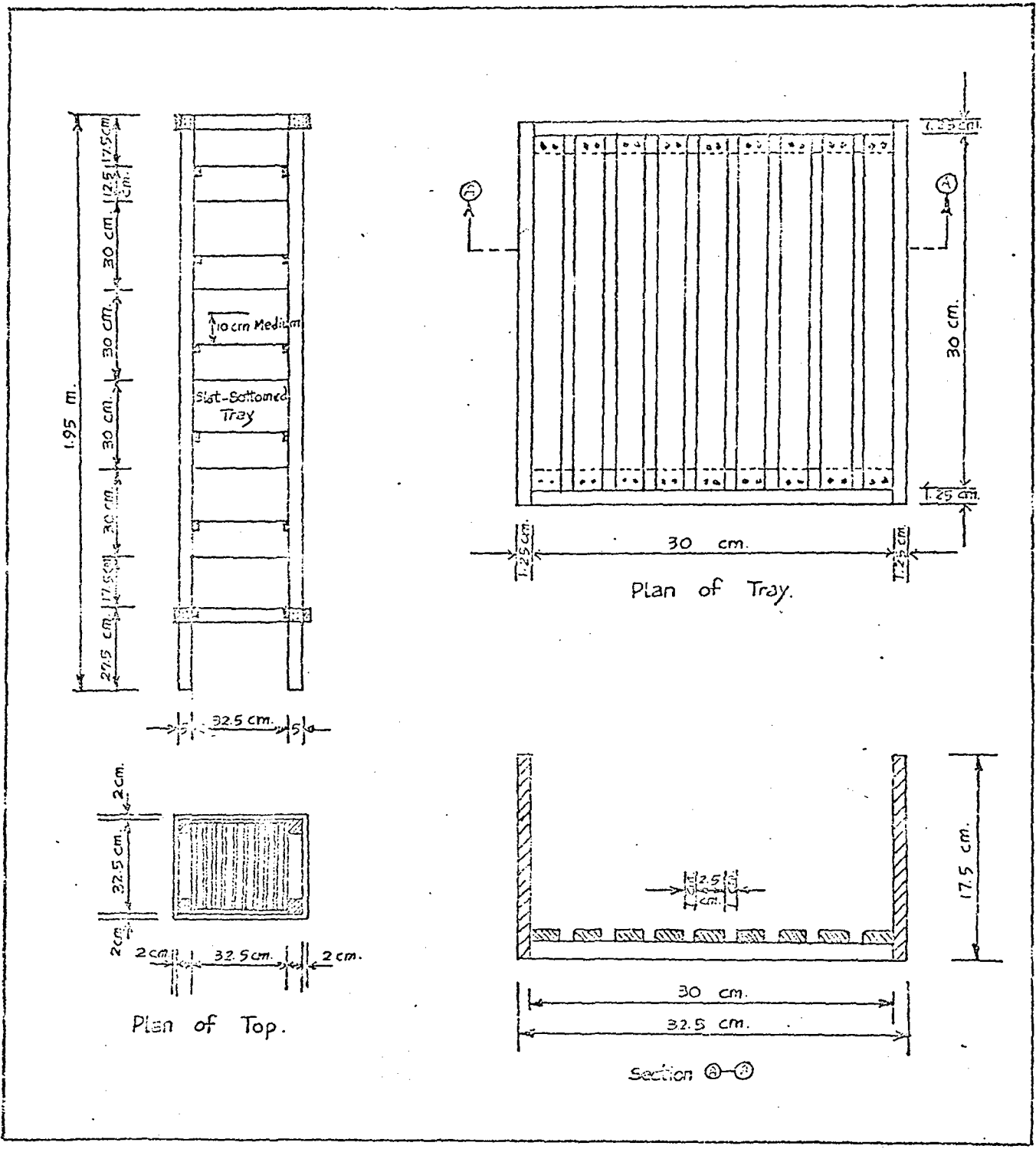


Fig. 2 — Details of Plant-Scale Aerator.

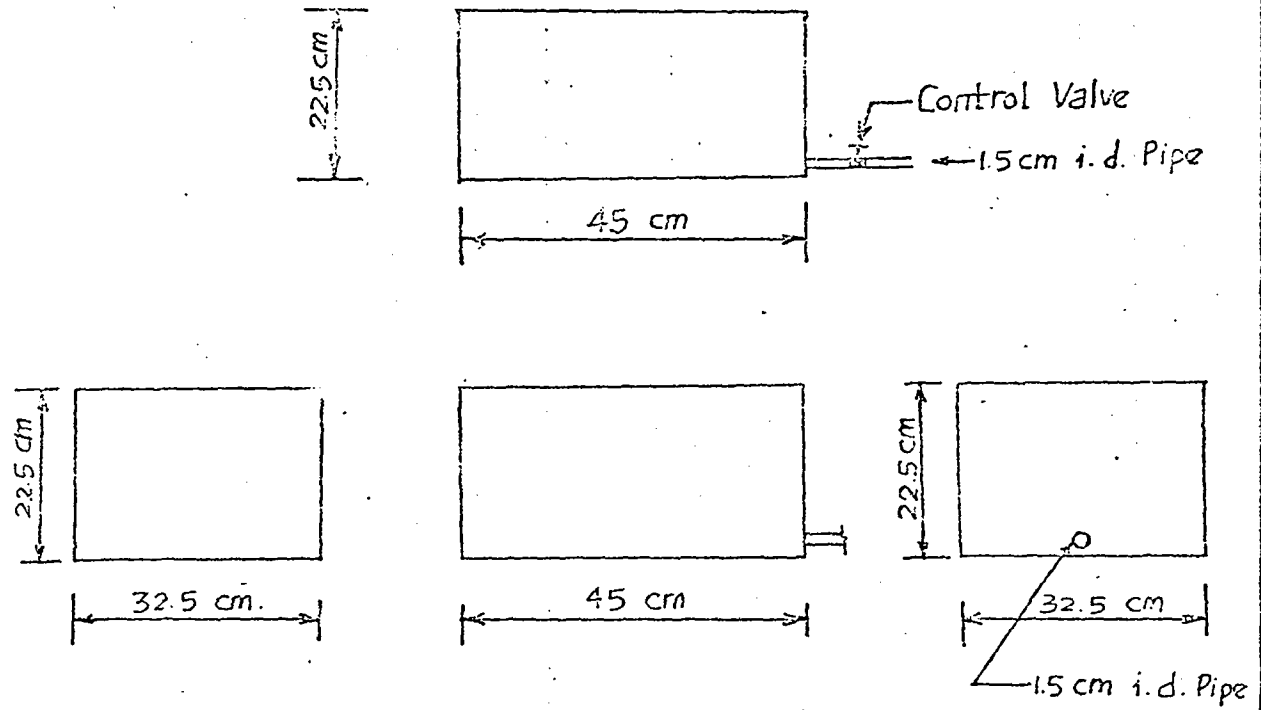


Fig. 3 — Details of By-Pass Chamber

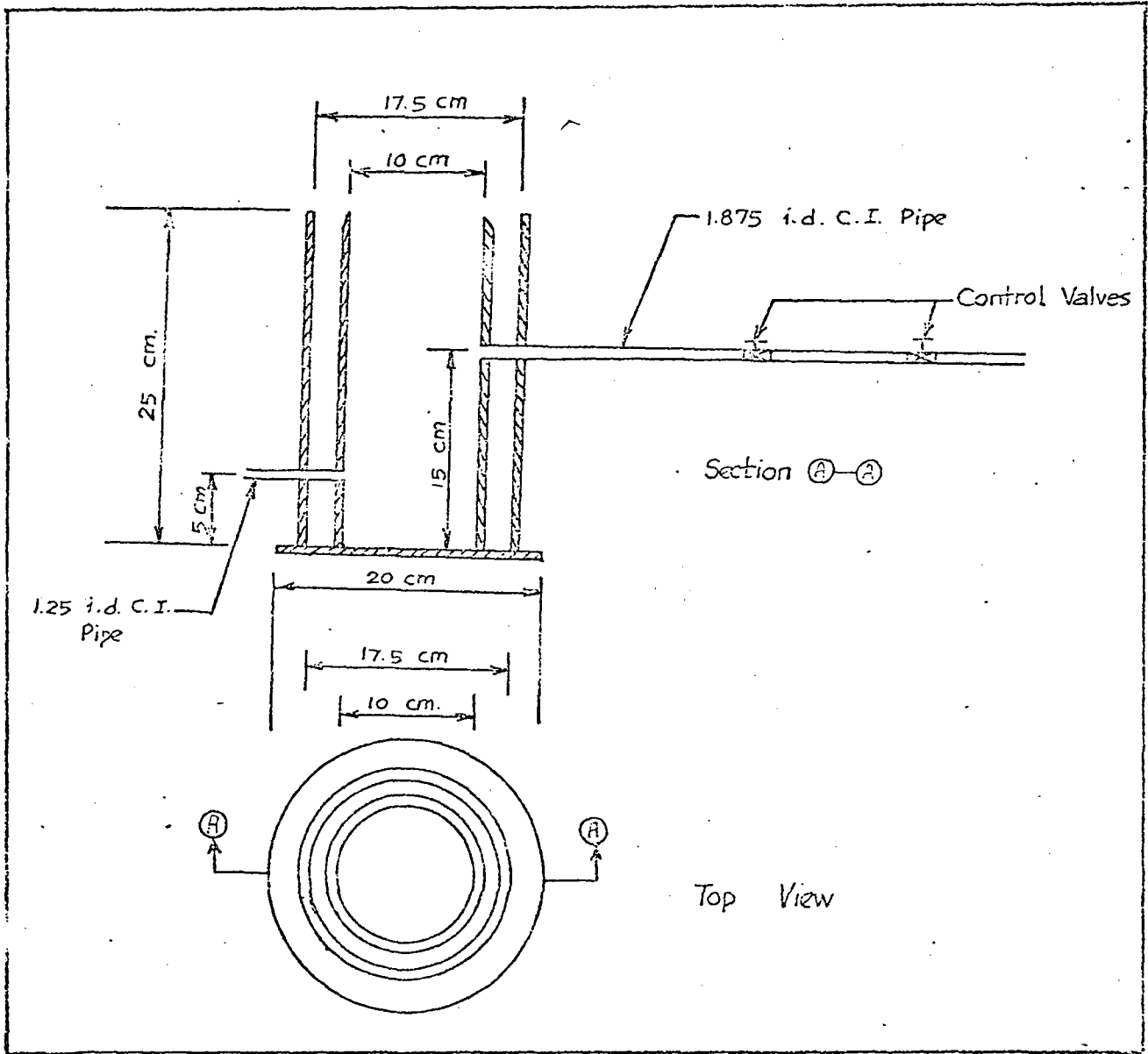


Fig. 4 - Details of Mixing Chamber.

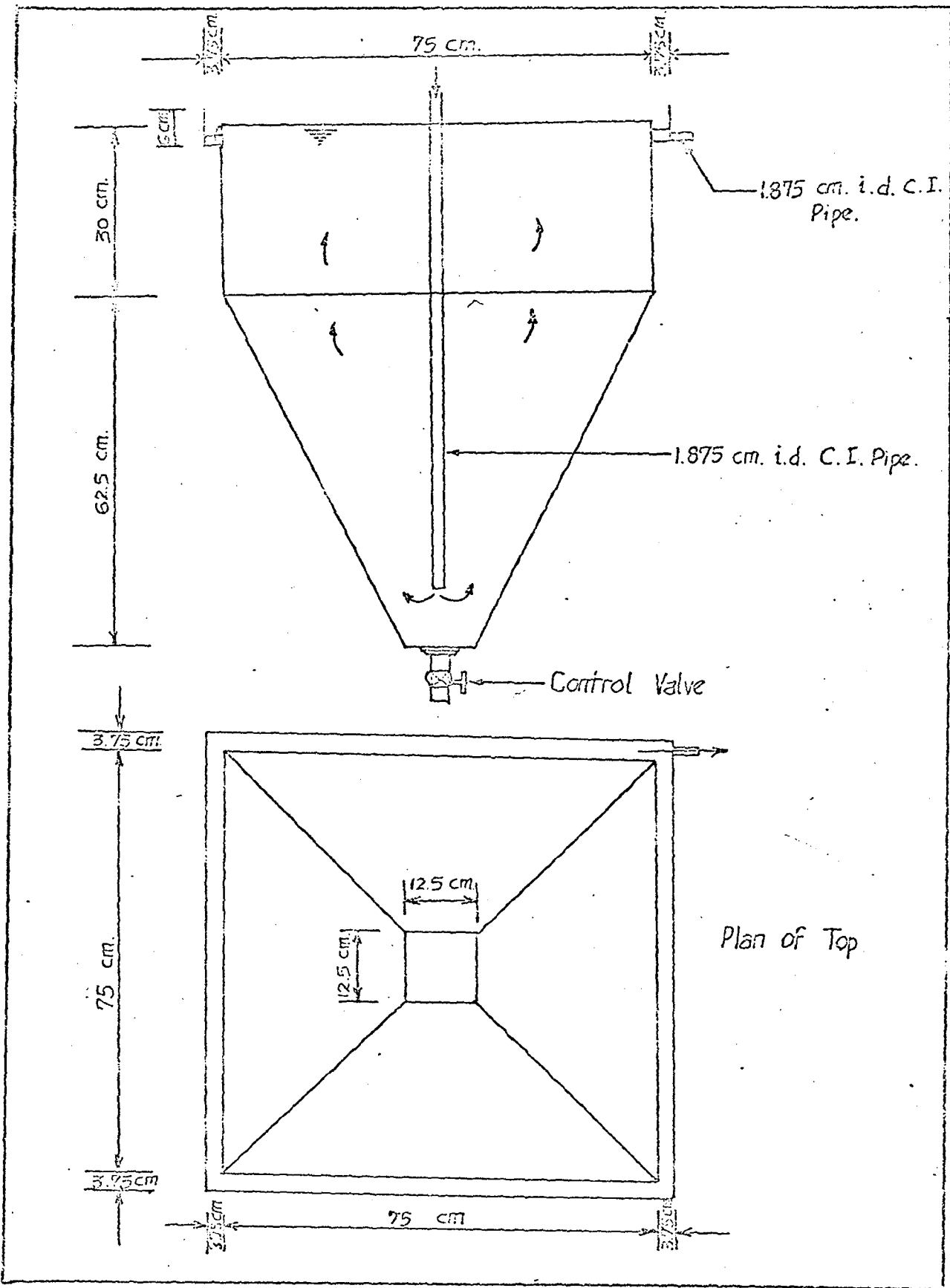


FIG. 5 — Details of Upflow Precipitator with Down-draught Tube.