WRC WATER RESEARCH CENTRE

TECHNICAL REPORT TR 13

WATER CLARIFICATION BY FLOTATION – 4

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November 1975

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CORRIGENDA

In Water Research Centre Technical Report TR13 "Water Clarification by Flotation - 4" please note:

Page 2,	Figure 1,	Should read WRC air injection nozzle, X.
Page 6		Last paragraph Should read . . . and 0.5 m high on . . .
Page 15,	Figure 9,	horizontal axis should read mg/l Fe.
Page 17,	Figure 11,	notation on graph lines should read 7 mg/l Fe 3 mg/l Al
Page 18,	Figure 13,	vertical axis should read mg/l Al.
Page 20,	Figure 16,	the note "Volume of air dissolved in water at atmospheric pressure" refers to the point at which the two graph lines meet the vertical axis.
Page 22,	Figure 18,	vertical axis should read mg/l Fe.
Page 23,	Figures 19 and 20,	the numbers against plotted points indicate nozzle identity.
Page 26,	Figure 21,	'Residual coagulant' is incorrectly arrowed to the line of connected inverted pyramid triangles. Residual coagulant is the line of connected pyramid triangles.
Page 35,	Figure 26,	the horizontal axis note PADDLE SPEED (rev/min) should read $\left[\text{PADDLE SPEED (rev/min)}\right]^2$

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WATER CLARIFICATION BY FLOTATION—4

Design and experimental studies on a dissolved-air flotation pilot plant treating 8.2 m^3/h of River Thames water

by

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Page 38	Ref. 4.	STANDER, C.J. should read STANDER, G.J. VAN BLERK, S.N.V. should read VAN BLERK, S.H.V.
Page 39	Ref. 12.	the date of this reference should read 1962

CONTENTS

1. INTRODUCTION

A detailed review of the literature (1) provided sufficient evidence of the potential value of dissolved-air flotation to warrant further study of the process. Subsequent laboratory investigations (2) confirmed the technical feasibility of floating many different types of water clarification floc, including those resulting from the coagulation of waters heavily laden with algae, coloured waters and turbid waters with a very low organic content. With all these natural waters, flotation was achieved without the addition of any chemicals other than those normally used in coagulation.

Following this work, a pilot-scale flotation plant was constructed for the treatment of 1.8 m^3/h of River Thames water (3). A round conical-bottomed flotation tank, similar to that employed by van Vuuren (4) for water reclamation studies in South Africa, was used and its performance was studied from June 1971 until June 1972. These investigations showed that dissolved-air flotation was a technically feasible alternative to sedimentation for the clarification of a lowland river water such as the Thames. The chemical treatment for flotation was basically the same as for sedimentation and no special additives were required. In contrast to upflow sedimentation, however, dissolved-air flotation required a separate preliminary flocculation stage. Efficient flotation was found to require the addition to the flocculated water of 4 to 6% by volume of water saturated with air at 345 kPa. The efficiency of water clarification by flotation as judged by colour, turbidity and residual coagulant concentrations was shown to be as good as that from a well operated sedimentation tank, and algal removal was better.

Flotation was a much more rapid process than sedimentation, even when the time for flocculation was taken into account. An additional advantage of flotation was the production of a sludge having a much higher solids content than that obtained directly from a sedimentation tank. Solids contents ranging from 2 to 10% were obtained, depending on raw water quality and the method of sludge removal.

A second pilot plant, treating 8.2 m^3/h of River Thames water, has been used to study the effect of flocculation, dissolved-air addition, coagulant dose, plant throughput and raw water quality on treated water quality. The flocculation and aeration systems were of similar design to those of the first pilot plant but a rectangular, flat-bottomed flotation tank was used (Figures 1 and 2) in order to simplify scaling-up the design of future plant. The results of these investigations over the period March 1973 to March 1975 are the subject of this report.

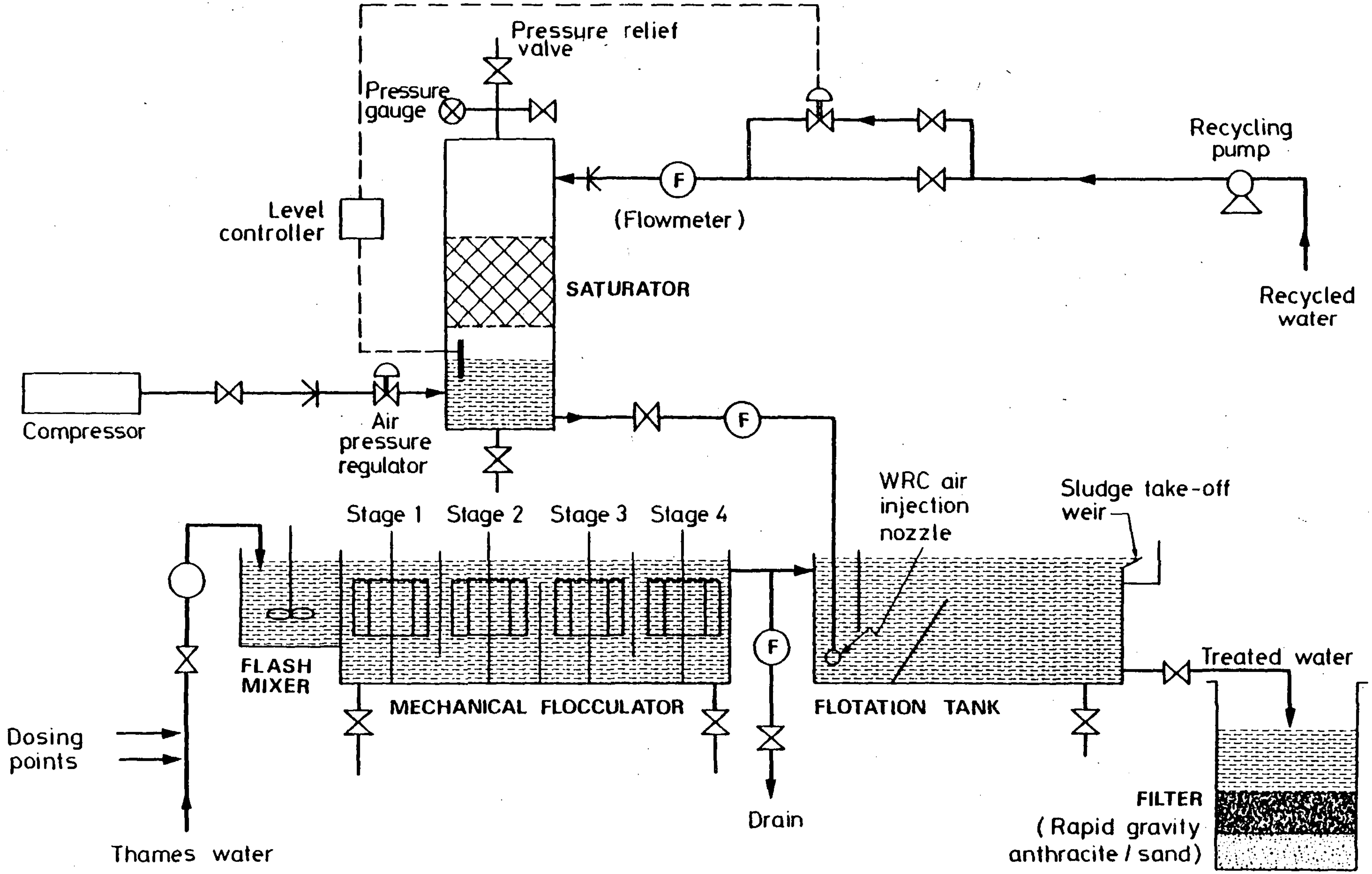

Figure 1. Flow diagram of the 8.2 m^3/h flotation pilot plant

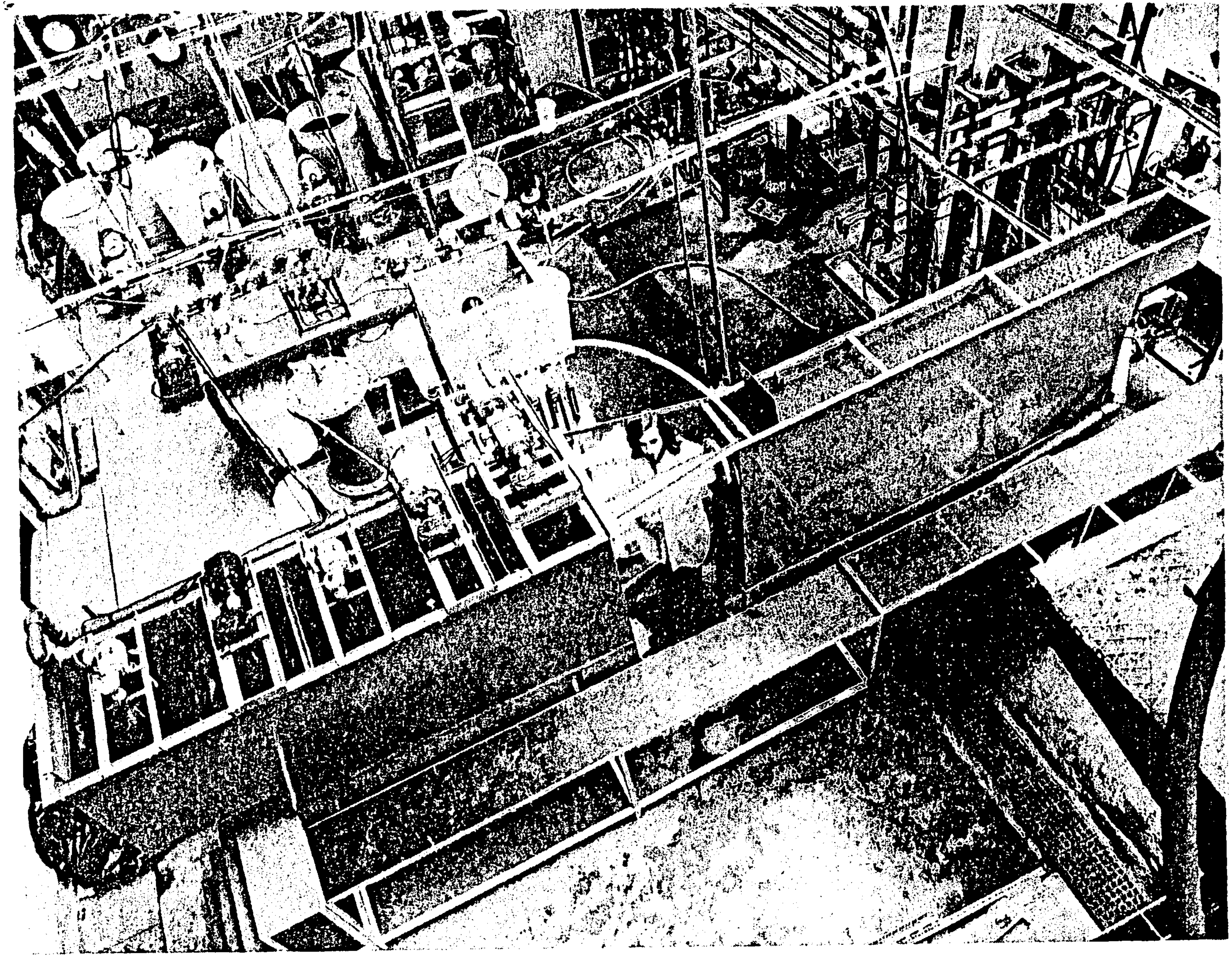

Figure 2. The 8.2 m³/h flotation pilot plant

2. EXPERIMENTAL

2.1. RAW WATER

River Thames water quality varied considerably during the period of investigation. For most of the time the raw water turbidity was below 10 FTU (Figure 3) and the colour was 10 to 15° Hazen but during flood conditions the turbidity rose to 100 FTU and the colour to 45° Hazen. Suspended solids varied from a normal of 20 to 30 mg/l to over 120 mg/l, temperature from 4 to 22°C and orthophosphates from 0.2 to 1.6 mg/l P. Algae were only apparent in large numbers during April/May 1974 (Figure 4). The maximum count recorded was 145 000 small centric diatoms/ml (predominantly Stephanodiscus Hantzschii) with a corresponding chlorophyll a maximum of 226 μg/l. During this period the raw water pH rose from the normal 7.5 to 8 to over 9.

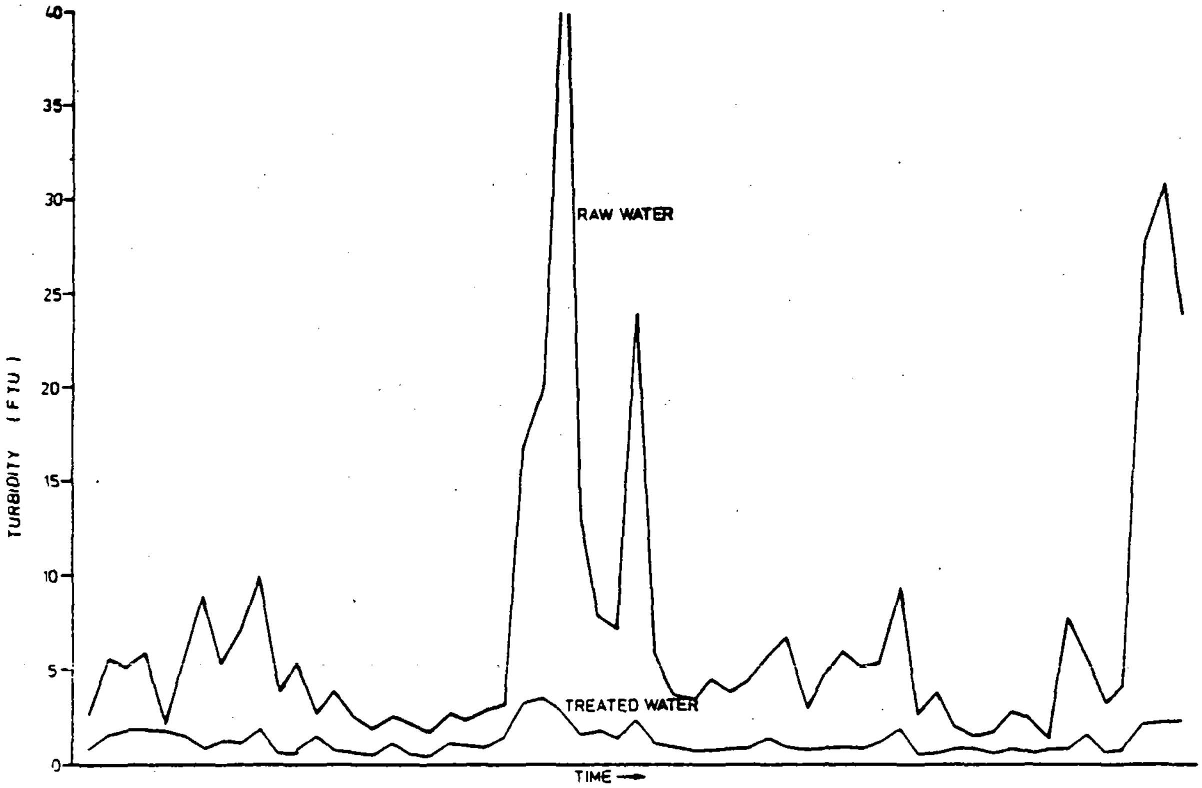

Figure 3. Raw and treated water turbidity between March 1973 and March 1975

2.2. CHEMICAL TREATMENT

Two alternative coagulants, aluminium sulphate and ferric sulphate, were used in this work. Sulphuric acid was used to adjust the pH when required and, during the algal bloom of April/May 1974, the raw water was prechlorinated using sodium hypochlorite.

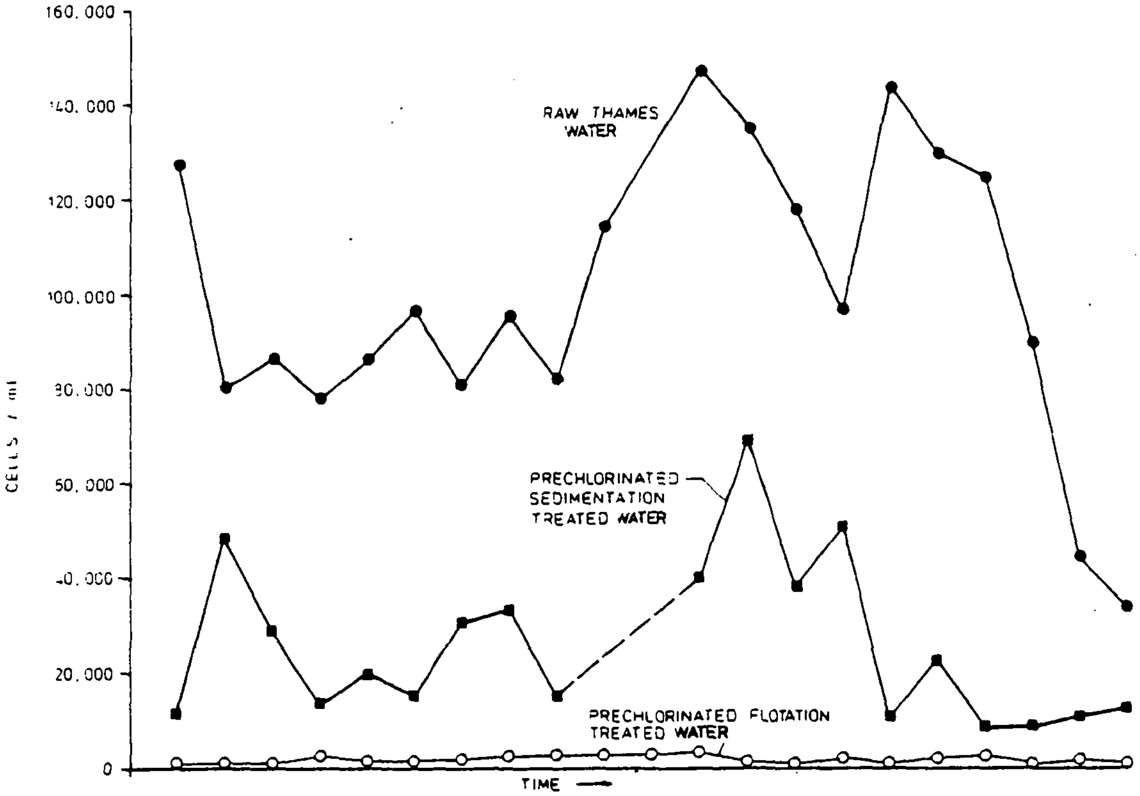

Figure 4. Algal bloom of small centric diatoms (Stephanodiscus Hantzschii) during April and May 1974

Aluminium sulphate solutions were made by dissolving the solid in tap water to give a final concentration of 1 to 2.5% w/v Al.

When this coagulant was used, the pH of the raw water was adjusted to approximately 6.8 by dosing 10% w/v sulphuric acid at the same point as the coagulant. Stock ferric sulphate solutions of 3 to 6% w/v Fe were prepared by diluting a commercial solution containing 18% w/v Fe. Sodium hypochlorite was supplied as a solution containing 15% w/v chlorine; this was diluted using tap water to give a stock solution of 7.5% w/v chlorine.

Chemicals were dosed using variable stroke metering pumps. Coagulants and acid were added to the raw water supply 15 seconds before flash mixing and sodium hypochlorite, when used, was dosed 15 seconds before coagulant addition. The coagulant doses used during the period of these investigations varied from 2 to 14 mg/l Fe (Figure 5) and 1 to 15 mg/l Al.

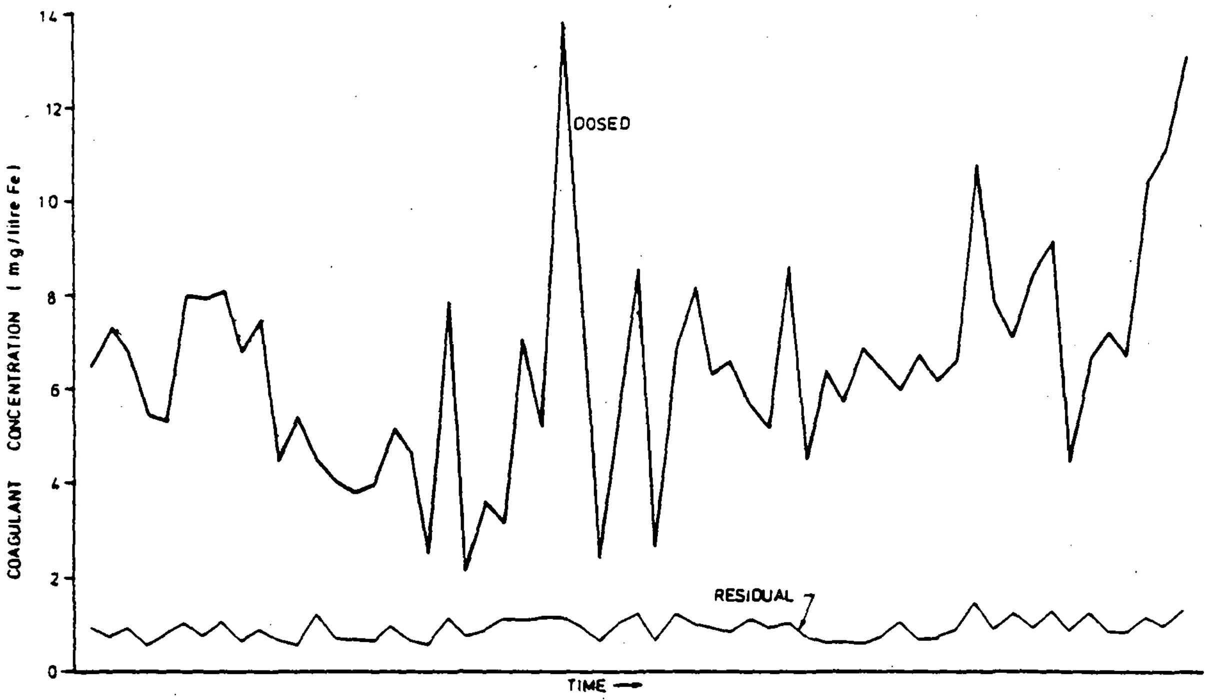

Figure 5. Dosed and residual coagulant (mg/litre Fe) between March 1973 and March 1975

2.3. THE PILOT PLANT

The design parameters of the 8.2 m^3/h dissolved-air flotation plant (Figure 1) were based on previous work carried out on the smaller pilot plant (3).

2.3.1. Flocculator.

The flocculator unit consisted of a flash mixer followed by four-stage mechanical flocculation. The flash mixer was a 0.6 m x 0.6 m x 0.75 m deep tank with a 0.65 m water depth. Mixing was achieved with a four-blade basic paddle 0.15 m diameter, each blade 0.015 m wide on a 0.01 m shaft driven at 340 rev/min. The flocculator consisted of a tank 1.8 m x 0.6 m x 1.2 m deep divided by partial baffles into four sections each 0.45 m x 0.6 m x 1.2 m with a water depth of 1.1 m (Figure 1).

Water flowed from the flash mixer over the first baffle 0.35 m beneath the water surface into the first-stage flocculator, under the second baffle 0.3 m from the base of the tank into the second-stage flocculator, over the third baffle and under the fourth baffle 0.35 m from the water surface and 0.3 m from the tank base.

The four flocculator paddles were gate paddles consisting of four PVC blades each 0.06 m wide and 0.7 m high on a 0.01 m shaft. The diameter of the paddle was 0.3 m. Each paddle was driven by an electric motor via a right-angle reduction-gear-box. Initially the paddle speeds used were 57, 39, 28 and 18 rev/min for stages 1, 2, 3 and 4 respectively. Later, variable speed drive units were used to enable the effects of different paddle speeds to be investigated.

The flocculator was connected to the flotation tank by a 0.15 m diameter PVC pipe and a proportion of the flocculated water could be diverted to a drain if desired.

2.3.2. Flotation tank.

The flotation tank was a flat-bottomed vessel 2.4 m x 0.3 m x 1.2 m deep containing two baffle plates. The baffles were movable and several baffle lengths were available to give flexibility to the system. Initially they were placed vertically at 0.2 and 0.4 m from the flocculated water inlet with a 0.2 m gap beneath the first baffle and a 0.3 m gap between the second baffle and the water surface, the water depth being 1.1 m. The depth of the flotation tank could be halved by fitting a false bottom. A Perspex observation window 1.25 m x 0.7 m was placed in one wall of the flotation tank.

The water level in the flocculator and flotation tank was maintained using an adjustable-level control weir.

Floated sludge was initially removed by manual skimming but later an electrically-driven skimmer consisting of a chain drive and 16 blades 0.12 m x 0.3 m wide at 0.3 m spacings was used. The skimmer rate could be varied from 0.3 to 3.0 m/min and continuous or intermittent skimming was possible. A timing unit was used to control the frequency and duration of skimming. A sludge receiving trough 0.4 m x 0.3 m x 0.3 m deep was placed at the outlet end of the flotation tank and was fitted with an inclined 'beach' to facilitate sludge removal.

2.3.3. Filter.

The filters used after flotation were rapid-gravity, anthracite/sand filters. The construction and operation of the filters used was similar to those described in an earlier WRA report (5), except that their diameters were 0.3 m instead of 0.15 m. The filters contained 0.45 m of 16 to 32 mesh filter sand and 0.3 m of No. 2 NCB anthracite.

2.3.4. Saturator system.

The pressure vessel used for saturating water with air was 0.3 m diameter and 1.35 m high with dished ends top and bottom. The vessel was packed with a 0.75 m layer of 0.025 m diameter Berl saddles above a 0.3 m deep water reservoir.

The saturator system is shown in outline in Figure 1. Water was introduced to the top of the vessel via a multi-stage centrifugal pump and a variable-area flowmeter. Compressed air was introduced into the vessel just beneath the packing from an oil-less compressor via a non-return valve and a pressure-regulating valve. The compressor was set to operate between 550 and 690 kPa and the regulating valve was used to reduce the pressure to that desired for experimental purposes.

Water saturated with air was removed continuously from the base of the column via a second variable-area flowmeter. The level in the saturator vessel was controlled by means of three conductivity probes; an earth and high and low level detectors. As the water level fell below the low level detector an electrical circuit was broken which in turn activated the solenoid valve and allowed more water to pass into the saturator. Water passing the high level control completed a second electrical circuit; this deactivated the solenoid valve and resulted in a falling water level in the saturator. In this way the level in the saturator was controlled to ∓ 0.05 m from a given base line.

The dissolved-air stream was kept under pressure up to the point of injection, X (Figure 1) in the downflow section of the flotation tank. Initially, the flow from the saturation was controlled by a needle valve at X across which the pressure dropped to atmospheric, thereby releasing the dissolved air. It was found however that needle valves were subject to erosion leading to poor flow distribution and inadequate deaeration of the saturated water. Replacement of these valves could be costly and control on a larger plant with a great number of needle valves could be difficult.

A special nozzle was therefore developed (Figure 6) which incorporated a specially designed orifice, the size of which controlled the flow rate of the pressurized water, while the orifice cover reduced the velocity so that the floc was not broken up. A series of orifice plates (Numbers 1 to 6, Figure 7) were available to give a range of flows.

The nozzle, known as the WRC Air Injection Nozzle, is the subject of a patent application.

2.4. OPERATION OF THE PILOT PLANT

The plant was operated at a nominal raw water flow rate of 8.2 m^3/h. After coagulant addition, the dosed water was flash-mixed and subjected to four-stage, 'tapered' mechanical flocculation. 0.57 m^3/h of water saturated with air at 345 kPa was added to the flocculated stream in the down-flow section of the flotation tank (i.e. 7% recycle*).

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* In dissolved-air flotation it is common to express the flow from the saturation as a percentage of the flow to be treated and to term this the percentage recycle. This convention will be used throughout this report.

Figure 6. The WRC Air Injection Nozzle

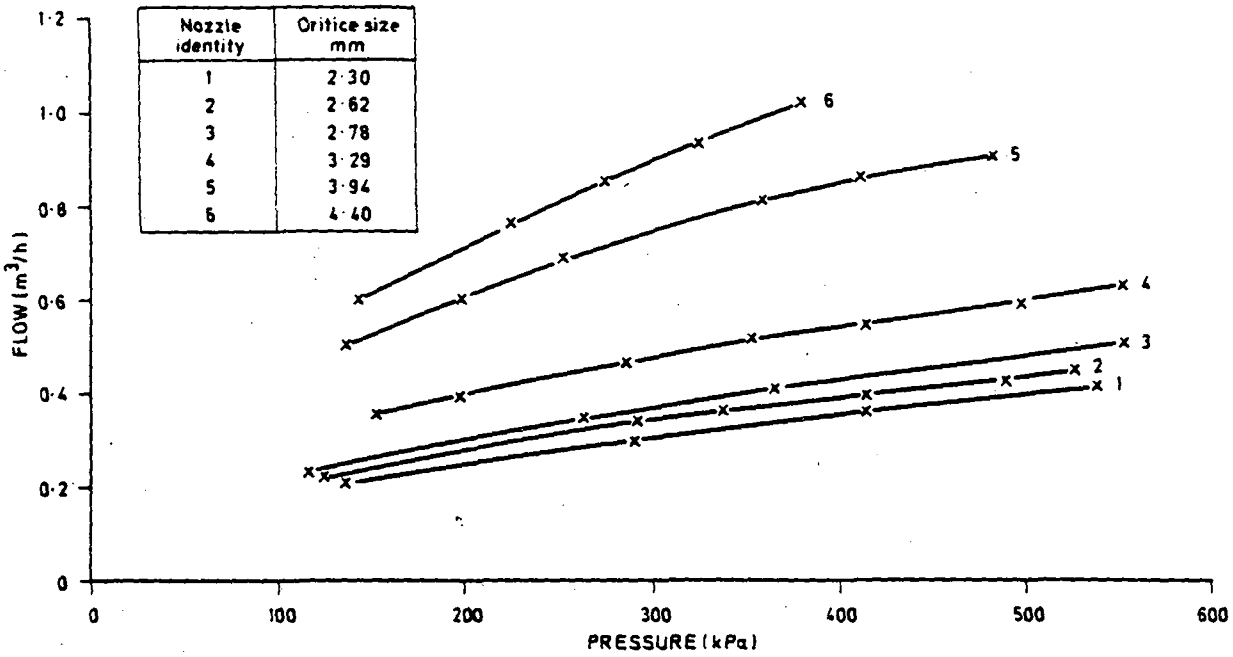

Figure 7. Flow through the WRC Air Injection Nozzle

As the pressure on the dissolved-air stream was reduced, air bubbles came out of solution and attached themselves to the pre-formed floc. The air/floc agglomerate rose rapidly in the up flow and horizontal flow section of the flotation tank forming a thick sludge on the water surface. The flotation-treated water was taken off at the base of the flotation tank and passed on to rapid gravity anthracite/sand filters.

Under these operating conditions there were $1\frac{1}{2}$ minutes of flash mixing, four stages of tapered mechanical flocculation at $2\frac{1}{4}$ minutes per stage, followed by $5\frac{1}{2}$ minutes flotation and rapid gravity anthracite/sand filtration at 2 mm/s (150 $g/ft^2/h$).

Sludge was removed from the flotation tank by the mechanical skimmer which was operated either continuously or intermittently.

2.4.1. Start-up and control.

A flow diagram of the pilot plant is shown in Figure 1.

Raw water was supplied to the plant through a 0.050 m PVC pipe, the flow being controlled by a diaphragm valve and monitored by a variable-area flowmeter.

All other valves were closed. Chemical dosing, the flash mixer and flocculators were started up as the raw water overflowed into the flotation tank. When the water level in the flotation tank had risen to within 0.3 m of the sludge off-take weir, the main outlet valve from the flotation tank was opened and the aeration system was started. To do this, the valves on the delivery and suction sides of the recycle pump and the saturator drain were opened, and the recycle pump was primed. The saturator drain and the valve on the delivery side of the recycle pump were then closed. The compressor was started and air was fed into the saturator. The pressure regulator on the compressor was set at 552 to 690 kPa (80 to 100 psig) and the pressure-reducing valve to 345 kPa. When the saturator pressure reached 345 kPa, the recycle pump was started and the valve on the delivery side of the pump was opened. When the 'high level' indicator was activated, the valve on the outlet from the saturator was fully opened and the flow was indicated on the flowmeter. The flow through the flowmeter on the inlet side of the saturator was then adjusted to approximately 90% of outlet flow, whilst the solenoid valve was still closed. When the 'low level' indicator was activated, a solenoid valve was automatically opened and the flow through the inlet flowmeter rose to approximately 120% of that of the outlet, the additional flow being controlled by the valve downstream of the solenoid valve.

The flow from the outlet of the saturator was controlled by a flow-controlling pressure-reducing device (Section 2.3.4.).

The flocculated water passed through a 0.150 m-diameter PVC pipe and the flow to the flotation tank was controlled by a valve on the flotation by-pass line. The flow through this line was measured by an orifice plate and manometer. The water level in the flotation tank was adjusted, using a level control weir, until it was at the upper edge of the sludge off-take weir. The sludge skimmer was then started, the speed being controlled by a continuously-variable drive unit.

The treated water was then passed to rapid gravity anthracite/sand filters via a header tank. The flow onto the filter was controlled, using a diaphragm valve at the base of the header tank, to the desired rate of 2 mm/s.

2.4.2. Sampling and analysis.

With the flotation plant operating as described in Section 2.4.1. the performance was compared with that of a 1.2 m square, hopper-bottomed upflow floc blanket clarifier, operating at an upflow rate of 2 to 4 m/h, followed by a rapid gravity anthracite/sand filter operating at 2 mm/s.

Samples of raw, dosed, treated and filtered water were analysed as summarized in Table 1.

Table 1. Summary of sampling and analysis

Sample	Raw water	Flotation plant Dosed	Flotation plant Treated	Flotation plant Filtered	Floc blanket clarifier Dosed	Floc blanket clarifier Treated	Floc blanket clarifier Filtered
pH	✓	-	✓	✓	-	✓	✓
Colour °H	✓	-	✓	✓	-	✓	✓
Turbidity FTU	✓	-	✓	✓	-	✓	✓
Temperature °C	✓	-	✓	✓	-	✓	✓
Coagulant mg/l	-	✓	✓	✓	✓	✓	✓
Algae cells/ml	✓	-	✓	✓	-	✓	✓
Chlorophyll a μg/l	✓	-	✓	✓	-	✓	✓
Suspended solids	✓	-	✓	✓	-	✓	✓

Turbidity, pH and residual coagulant determinations were made as described elsewhere (3)(6)(7)(8). Colour was measured in degrees Hazen using an absorptiometric technique (9). Algal counting and chlorophyll a determinations were carried out using methods developed at the Water Research Association* (10) and suspended solids were determined by filtration (9). pH was measured on an EIL 2320 pH meter and raw, treated and filtered water turbidities were measured on a Hach 2100A turbidimeter. A Sigrist photometer T65 was used for continuous monitoring of treated and filtered water turbidities. Filter headloss development was measured and recorded continuously using a Bell and Howell Dataran Type 4 pressure transducer and a Honeywell chart recorder.

Duplicate samples of sludge were weighed in tared dishes and dried to constant weight at 105°C. Values of the percentage non-volatile solids in the original samples were then determined.

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* Now the Water Research Centre

3. RESULTS

3.1. EFFECT OF RAW WATER QUALITY

Although the quality of the raw water varied considerably during the period of these investigations, this was not reflected in the treated water quality (Figures 3 and 5). Provided the optimum coagulant dose, pH, recycle rate and raw water throughput were employed, the flotation-treated water quality was usually comparable with that from an efficiently-operated floc blanket clarifier. Results obtained under deliberately inadequate treatment conditions have been omitted from Figures 3 and 5.

As reported previously (3), the treated water turbidity rarely exceeded 3 FTU even during periods of high raw water turbidities. Associated with these periods of high turbidity were increases in raw water colour from less than 15° Hazen to over 40° Hazen. Variations in the optimum coagulant dose from less than 5 mg/litre Fe to over 15 mg/litre Fe were required. Residual cation concentration figures, before filtration, were independent of optimum dose and varied from 0.5 to 1.5 mg/litre Fe (Figure 5). Alum doses varied from 2 to 8 mg/litre Al and residual figures from 0.5 to 0.9 mg/litre Al.

During April/May 1974 algal counts ranged from 30 000 to 150 000 cells/ml, the predominant species being small centric diatoms, mainly Stephanodiscus Hantzschii. The chlorophyll a for this period ranged from 20 to 226 µg/l. The algal counts after flotation, but before filtration, varied from 5000 to 15 000 cells/ml. The addition of 5 mg/litre Cl_2, in the form of sodium hypochlorite solution, prior to coagulant addition, resulted in algal counts in the flotation treated water of normally less than 1500 cells/ml and always less than 3000 cells/ml (Figure 4) provided the optimum coagulant dose, pH, recycle and throughput were being used. Floc blanket sedimentation operating under similar conditions at a rate of 2 m/h produced algal counts ranging from 8000 to 64 000 cells/ml. The instability of the sedimentation system was also reflected in the treated water turbidity and residual coagulant cation concentrations.

The ability of flotation to remove this type of algae from River Thames water was observed in earlier work carried out at the Centre (2)(3)(11).

Figure 8 shows the effect of chlorine dosing prior to coagulant addition, on algal counts in flotation-treated water. The optimum dose for this particular algal bloom was found to be 3 to 5 mg/litre Cl_2.

3.2. COAGULANT DOSE

A comparison was made between the coagulant dose required for the flotation pilot plant and that predicted by laboratory sedimentation jar test (12)(13).

The dose predicted by the jar test was found to be the most suitable dose for dissolved-air flotation (Figure 9). If the optimum dose was exceeded flotation-treated water quality deteriorated. The deterioration varied with raw water quality and the degree of over-dosing.

3.3. FLOCCULATION

Using paddle speeds of 57, 39, 28 and 18 rev/min, in stages 1, 2, 3, 4 respectively, it was found that by reducing the number of stages but maintaining the flocculation time of 9 minutes, there was a deterioration in treated water quality. The degree of deterioration was dependent on the number of stages in operation, but not on which stages were in operation. Table 2 shows the effect of the number of stages of flocculation on treated water quality and indicates a need for a minimum of three-stage mechanical flocculation.

Table 2. Effect of number of stages of flocculation on treated water quality

Number of stages	Residual coagulant (mg/l Fe)	Turbidity (FTU)
4	0.70 - 0.75	1.05 - 1.20
3	0.76 - 1.14	1.12 - 1.35
2	0.80 - 1.23	1.20 - 1.50
1	1.01 - 1.41	1.11 - 1.65
0	1.76	1.65

A series of experiments was carried out to investigate the effect on treated water quality of the ratios of paddle speeds in flocculator stages 1, 2, 3 and 4. These experiments were carried out at three discrete energy levels equivalent to the energy input for uniform flocculation (all paddles rotating at the same speed) at 20, 30 and 40 rev/min. It was assumed that energy input was proportional to the sum of the cubes of the paddle speeds (Appendix A). A summary of the paddle speed ratios and the paddle speeds used is also given in the Appendix.

The results (Table 3) showed that severely 'tapered' flocculation produced the poorest treated water quality. At the higher energy inputs an improvement in treated water quality was observed when uniform flocculation was changed to slightly tapered flocculation. At the three discrete energy levels used it was shown that a better

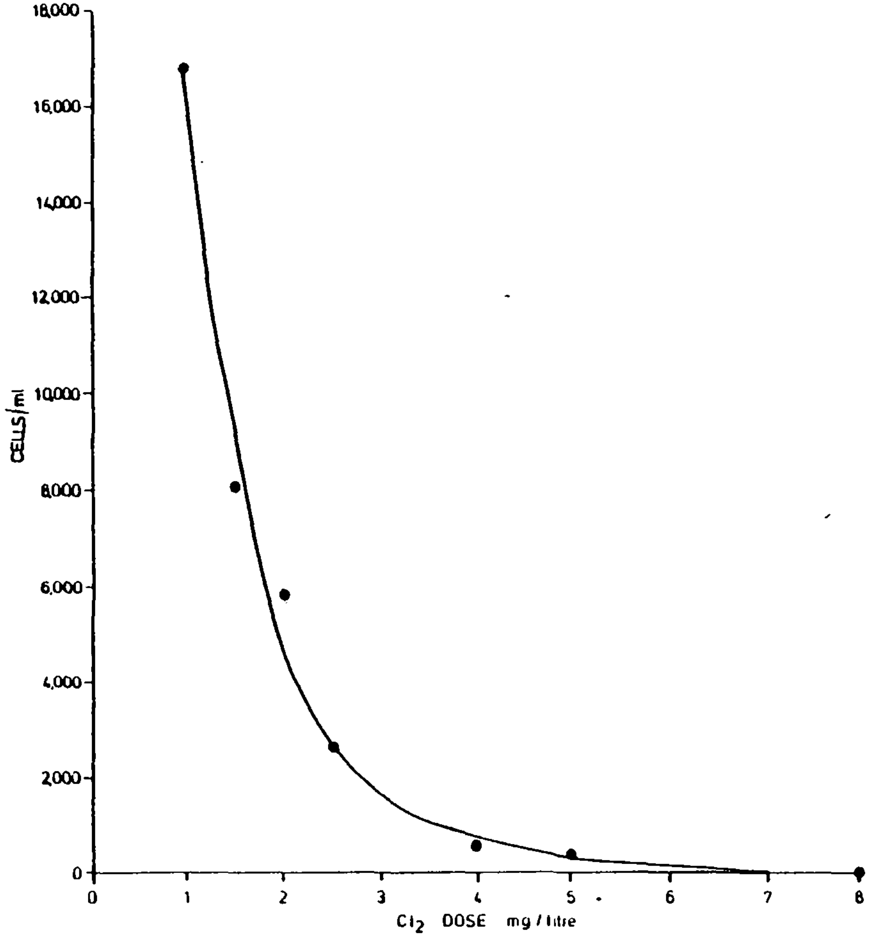

Figure 8. Variation in treated water quality with chlorine dose

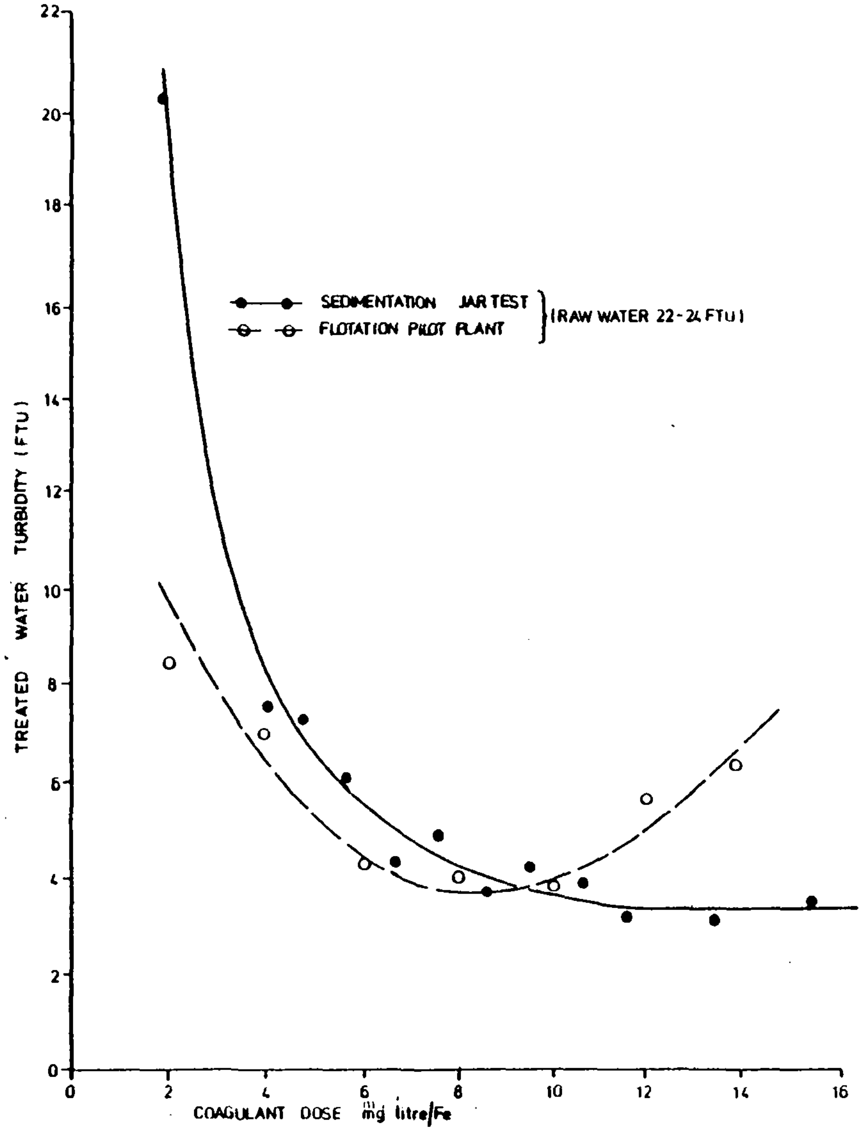

Figure 9. The effect of variation in coagulant dose on treated water turbidity; a comparison between sedimentation jar test and flotation pilot plant

treated water quality was produced at the higher energy inputs. The best treated water quality resulted when paddle speeds 47, 42.5, 37 and 29.5 rev/min were employed: that is paddle speed ratios of 1.6 : 1.45 : 1.25 : 1 at an energy input level equivalent to that of uniform flocculation at 40 rev/min.

Table 3. Effect of the ratio of paddle speeds and energy input on treated water quality

Energy input ≡ to uniform flocculation at	Paddle speed (ratio)	Residual coagulant (mg/l Fe)	Treated turbidity (FTU)
20 rev/min	1 : 1 : 1.25 : 1	0.70	0.70
	1.6 : 1.45 : 1.25 : 1	0.87	0.87
	2 : 1.6 : 1.25 : 1	1.02	0.92
	3 : 2.1 : 1.45 : 1	-	-
	4 : 3 : 2 : 1	1.04	0.91
	8 : 4 : 2 : 1	1.02	0.79
	27 : 9 : 3 : 1	1.14	0.92
30 rev/min	1 : 1 : 1 : 1	0.58	0.63
	1.6 : 1.45 : 1.25 : 1	0.56	0.62
	2 : 1.6 : 1.25 : 1	0.56	0.63
	3 : 2.1 : 1.45 : 1	0.60	0.63
	4 : 3 : 2 : 1	0.62	0.63
	8 : 4 : 2 : 1	0.79	0.74
	27 : 9 : 3 : 1	0.77	0.73
40 rev/min	1 : 1 : 1 : 1	0.55	0.63
	1.6 : 1.45 : 1.25 : 1	0.54	0.56
	2 : 1.6 : 1.25 : 1	0.56	0.58
	3 : 2.1 : 1.45 : 1	0.63	0.61
	4 : 3 : 2 : 1	0.71	0.63
	8 : 4 : 2 : 1	0.70	0.80
	27 : 9 : 3 : 1	0.77	0.73

3.4. AIR REQUIREMENT

A series of experiments was carried out to determine the effect on treated water quality of varying the percentage recycle. It was found (Figures 10 and 11) that when the recycled water was saturated with air at 345 kPa, the optimum recycle was between 6 and 8%. This confirms earlier WRC work (3). If the recycle exceeded 8% a deterioration in treated water quality could occur and this was most apparent when the raw water turbidity, colour and the coagulant dose used were high (Figures 10 and 11).

It was found, when using the WRC nozzle, that if the flow of saturated water was controlled using a valve upstream of the nozzle, the pressure drop across the valve was sufficient to make air come out of solution before the nozzle. This led to bubble coalescence and resulted in a deterioration in treated water quality (Figures 12 and 13).

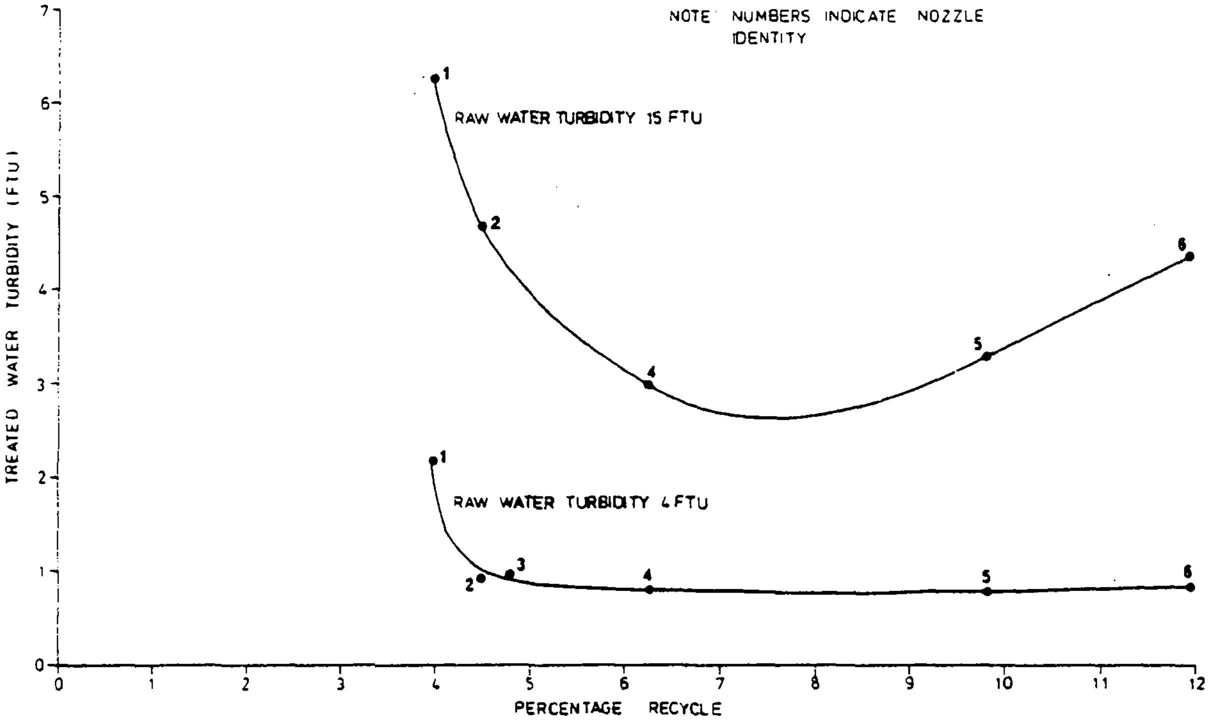

Figure 10. The effect of percentage recycle at 345 kPa on treated water turbidity

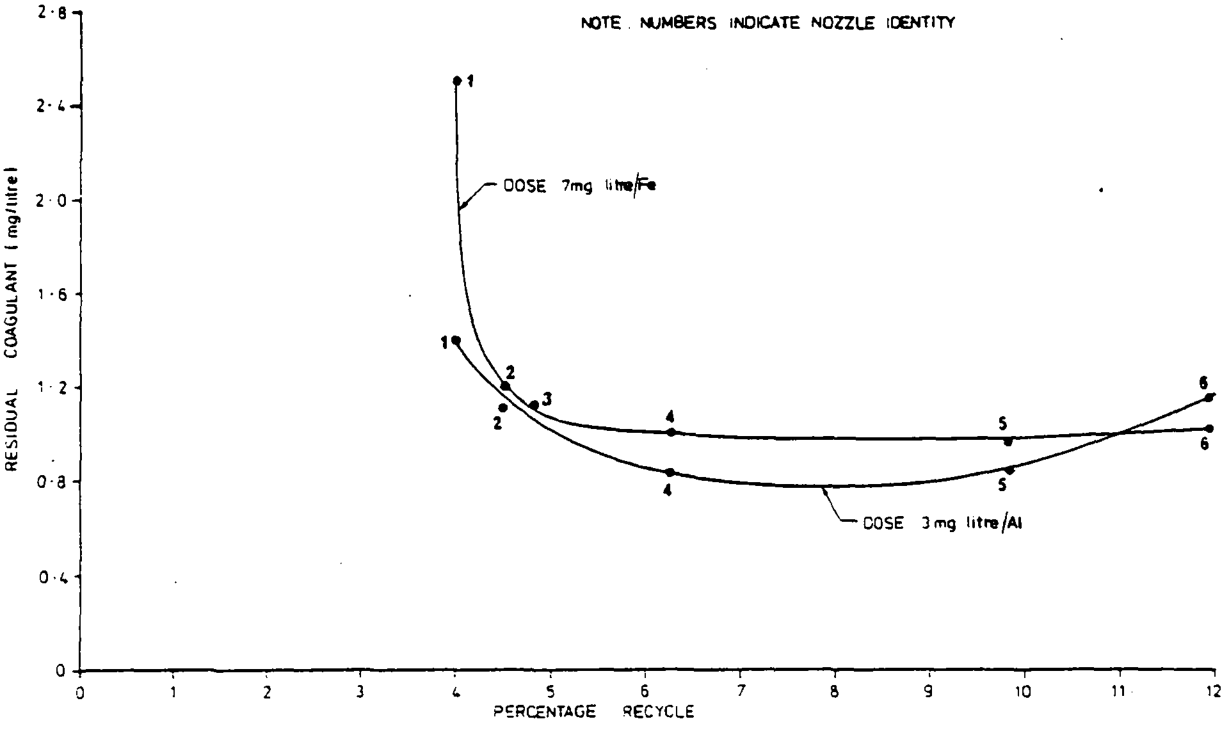

Figure 11. The effect of percentage recycle at 345 kPa on residual coagulant

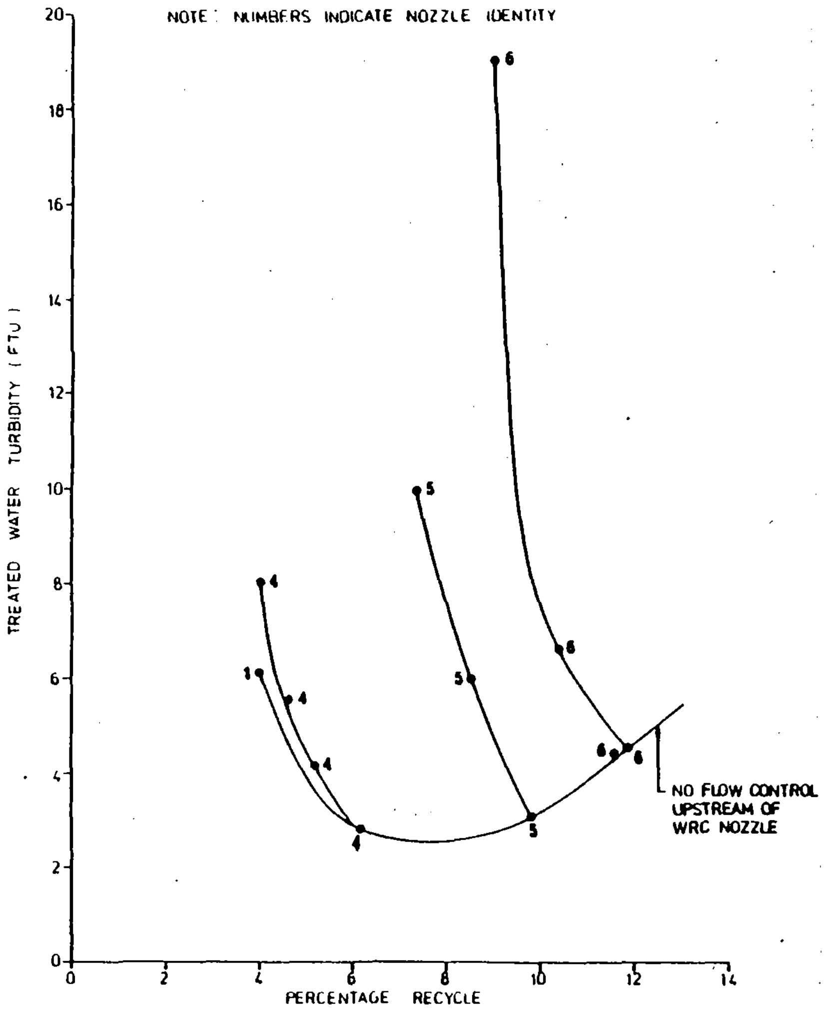

Figure 12. Treated water turbidity vs percentage recycle at 345 kPa; effect of controlling recycle flow upstream of WRC nozzle

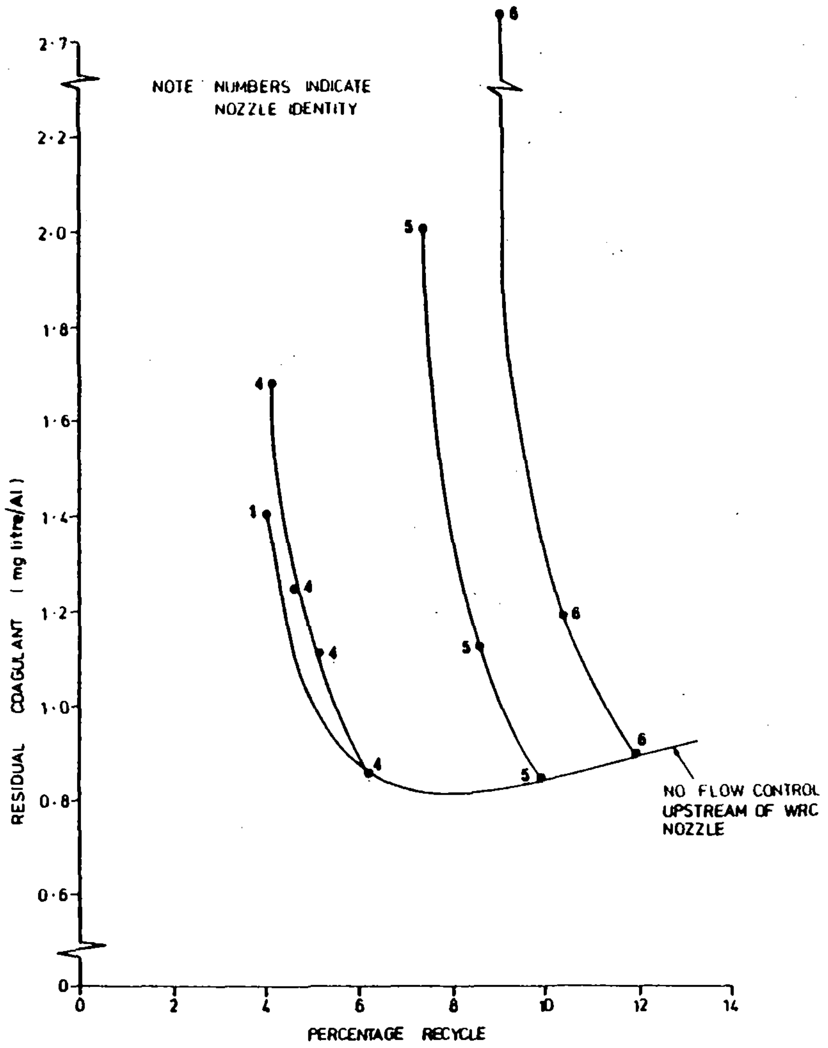

Figure 13. Residual coagulant vs percentage recycle at 345 kPa; effect of controlling recycle flow upstream of WRC nozzle

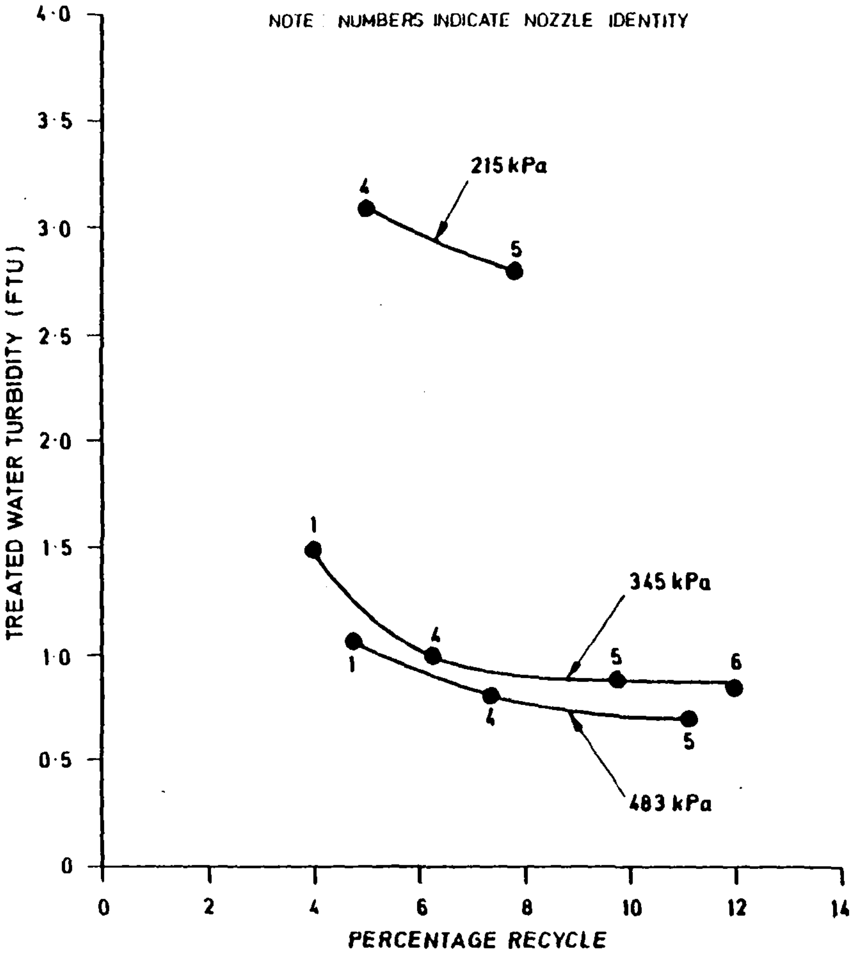

Figure 14. Treated water turbidity vs percentage recycle; effect of saturator pressure

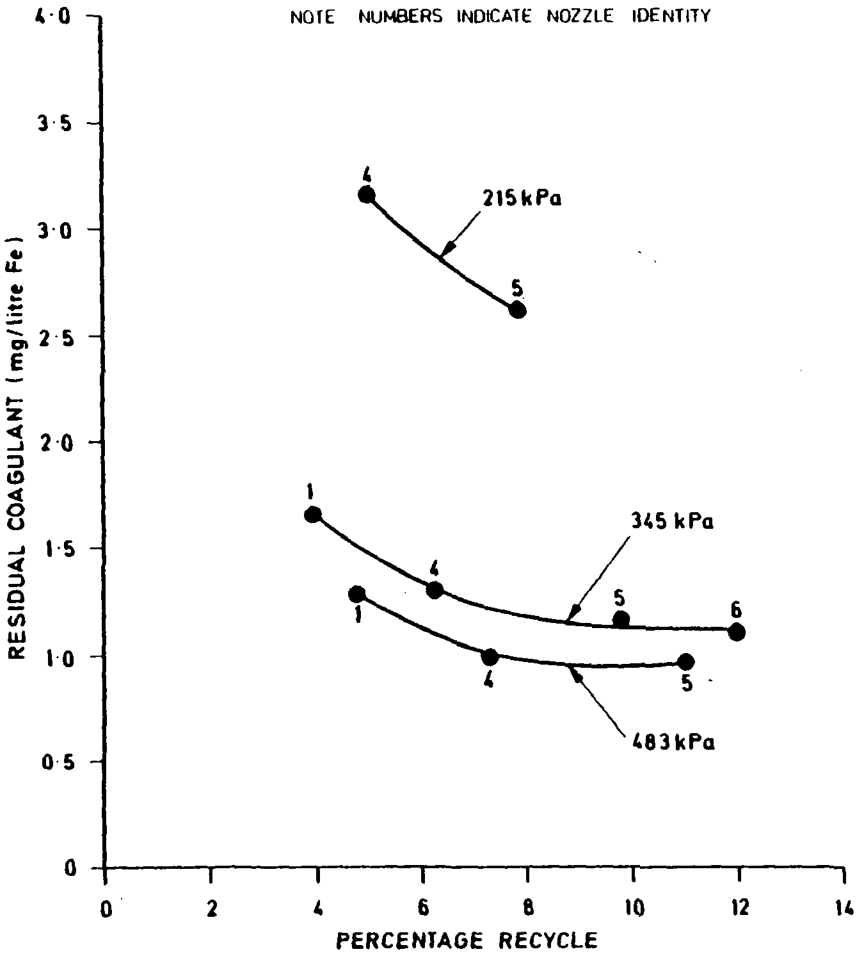

Figure 15. Residual coagulant vs percentage recycle; effect of saturator pressure

Increasing the saturator pressure from 215 to 483 kPa and thus increasing the air available for flotation, resulted in an improvement in treated water quality (Figures 14 and 15).

In order to compare the efficiency and the resulting effect on treated water quality, experiments were carried out using a packed and an unpacked saturator operating in the pressure range 150 to 500 kPa.

The flotation plant was operated in the conventional way with treated water being recycled via the pressurized packed saturator and WRC nozzle 4 (Section 2.3.4.) into the flocculated stream. The pressure in the saturator was varied over the range 150 to 500 kPa and samples of flotation-treated water were taken and analysed for turbidity and residual coagulant cation concentration. Samples of the recycled water as it left the saturator were collected and analysed for gas content by a technique developed at the WRC (14).

These experiments were repeated with an unpacked saturator.

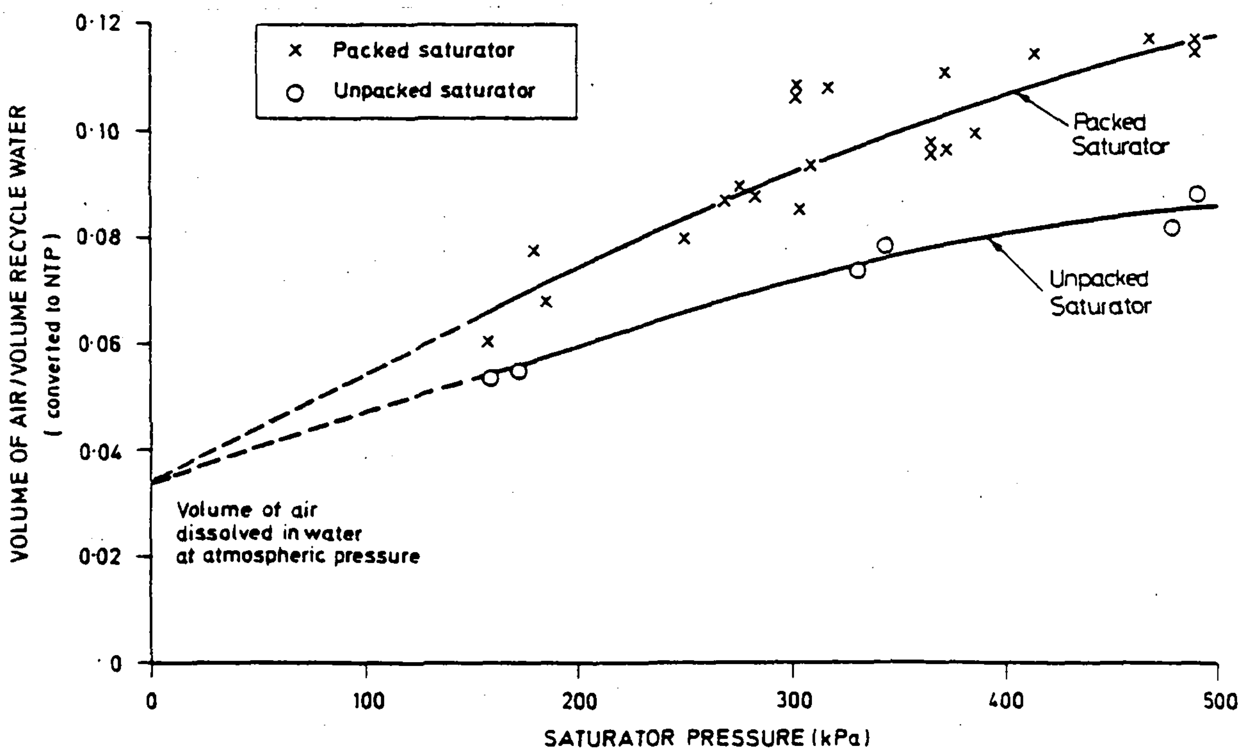

Figure 16. Effect of saturator pressure on volume of air dissolved in a unit volume of water; a comparison between packed and unpacked saturators (water temperature 11°C)

The results (Figure 16) show that the efficiency of the unpacked saturator was 60 to 65% of the efficiency of the packed saturator. The loss of efficiency of the saturator was reflected in the treated water quality (Figures 17 and 18) where, under similar operating conditions, the water quality produced when using a packed column was substantially better than that produced when using an unpacked column. In order to produce a similar product water quality when using an unpacked column it was necessary to increase the saturator pressure by 100 to 200 kPa (15 to 30 psig).

Figures 19 and 20 show that for treatment of 8.2 m^3/h of River Thames water the optimum volume of air required was 0.03 to 0.05 m^3/h. This optimum was found to be the same whatever the operating pressure of the saturator, percentage recycle and whether the saturator was packed or unpacked. The optimum was also found to be independent of raw water quality.

3.5. EFFECT OF THROUGHPUT

Earlier WRC work (2)(3) indicated that floc separation by dissolved-air flotation was a rapid process. The small-scale pilot plant (3) used to treat 1.8 m^3/h of River Thames water consisted of a 0.055 m^3 flash mixer, a 0.22 m^3 four-stage mechanical flocculator and a 0.6 m^3 hopper-bottomed flotation tank. The residence time in each of these three units was 1.8, 7.3 and 2.5 minutes respectively.

The pilot plant used in the present work (Section 2.3.) was designed to give 1.7 minutes flash mixing and 8.7 minutes flocculation when treating 8.2 m^3/h of River Thames water. The treatment time in the flotation tank could be varied from 5 to 25 minutes depending on the volume of flocculated water diverted to drain.

The results shown in Table 4 show that there was no significant effect on treated water quality as the residence time in the flotation tank was reduced from 25 to 5.4 minutes. These results were achieved with 7% recycle at 345 kPa.

Table 4. Effect of throughput in flotation tank on treated water quality

Flow through* flotation tank (m^3/h)	Residence time (minutes)	Coagulant concentration (mg/l Fe)		Turbidity (FTU)	
		dosed	treated	raw	treated
1.93	24.7	6.04	0.69	5.2	0.86
2.35	20.2	6.44	1.03	6.5	1.10
4.82	9.9	7.44	0.91	9.0	1.21
8.77	5.4	7.41	0.73	6.2	1.05

* Includes 7% recycle at 345 kPa.

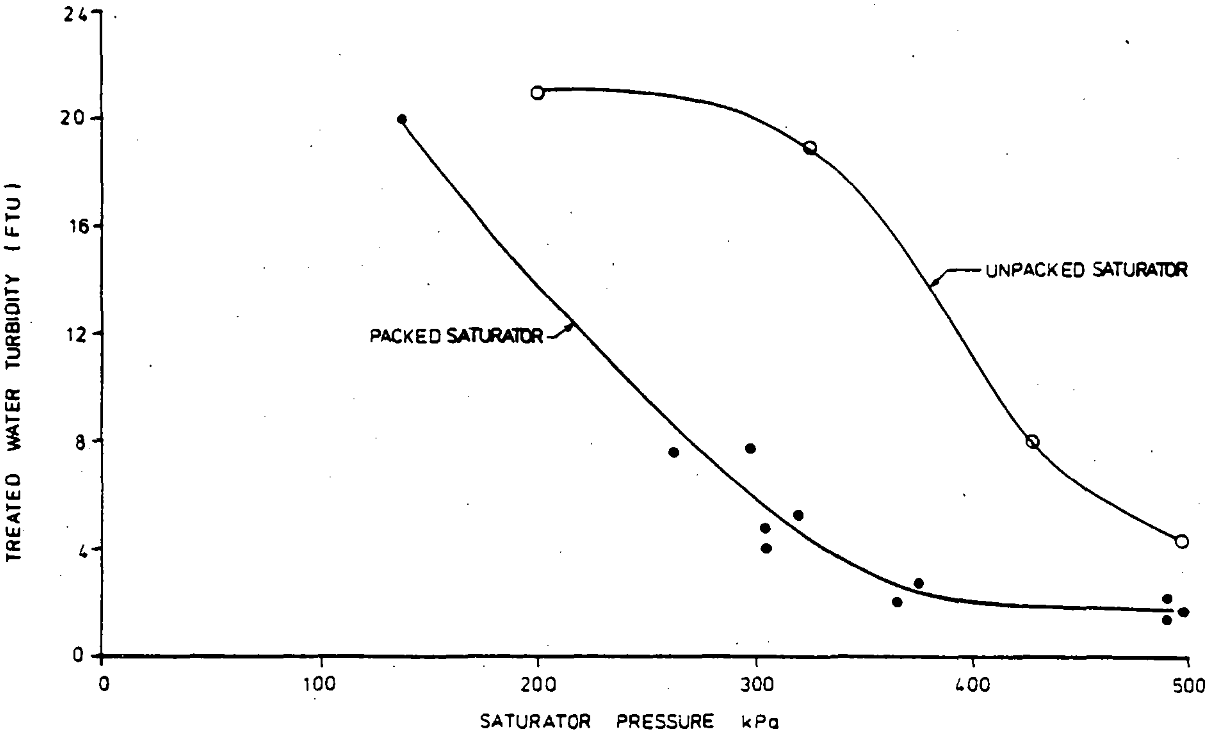

Figure 17. Effect of saturator pressure on treated water turbidity using WRC nozzle 4; a comparison between packed and unpacked saturators

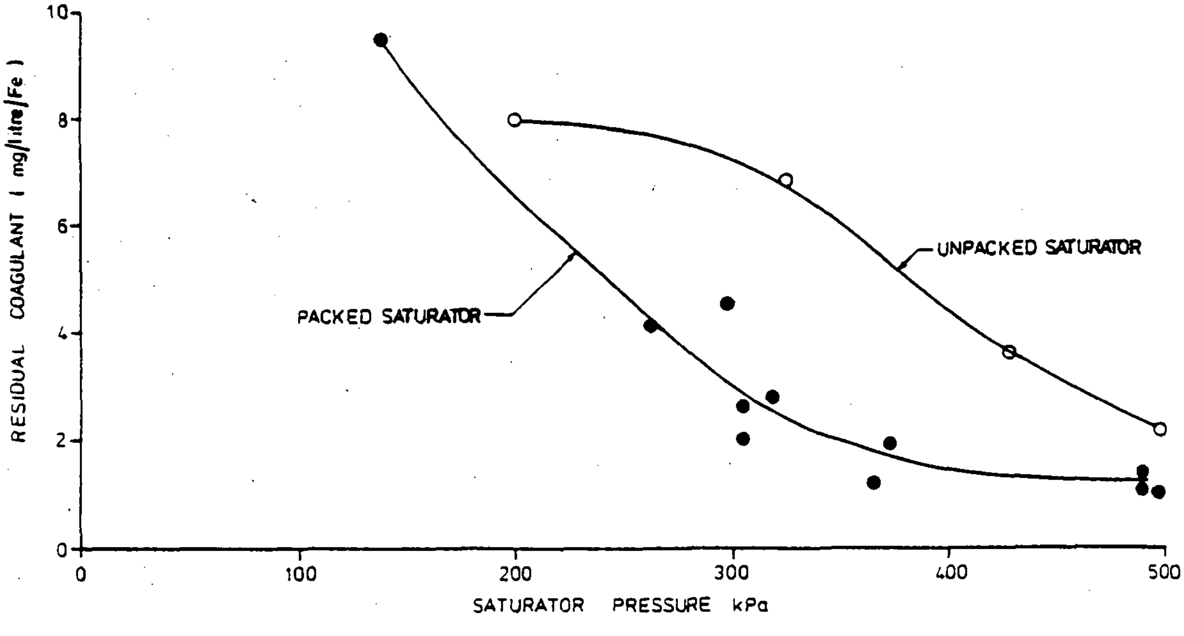

Figure 18. Effect of saturator pressure on residual coagulant using WRC nozzle 4; a comparison between packed and unpacked saturators

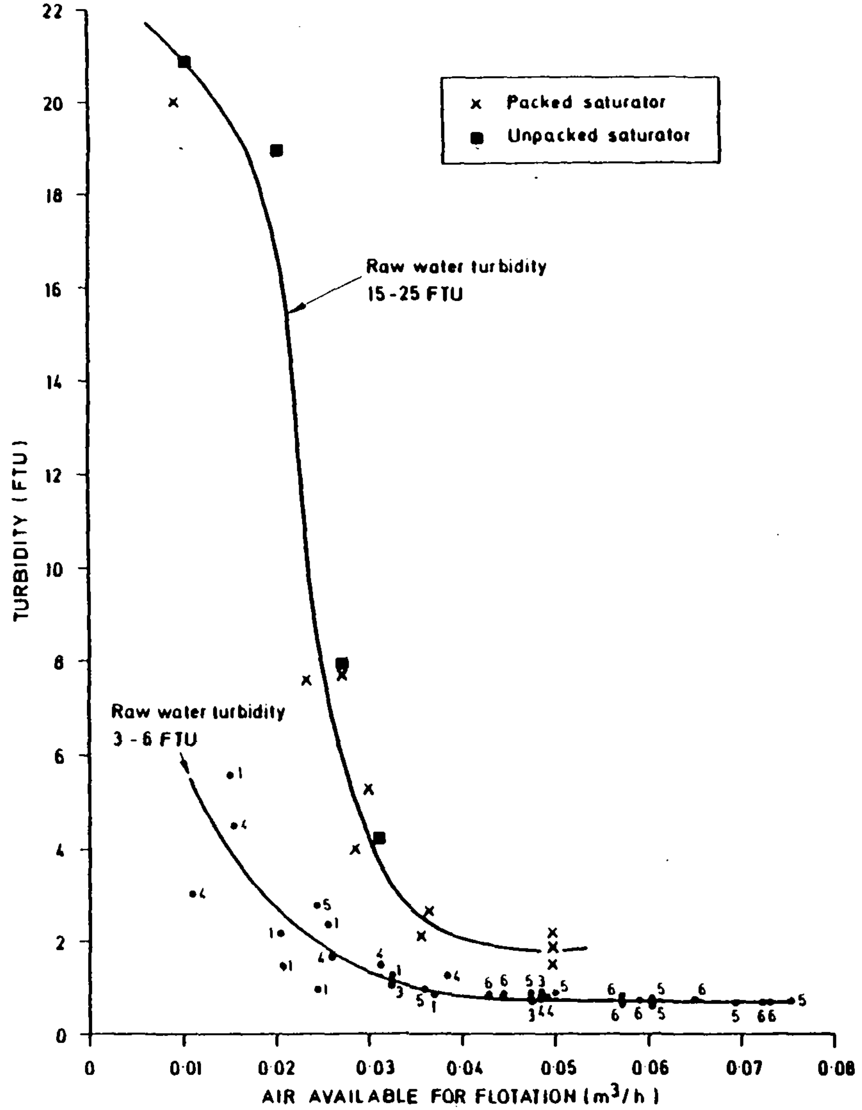

Figure 19. Effect of air available for flotation on treated water turbidity (plant throughput 8.2 m³/h River Thames water)

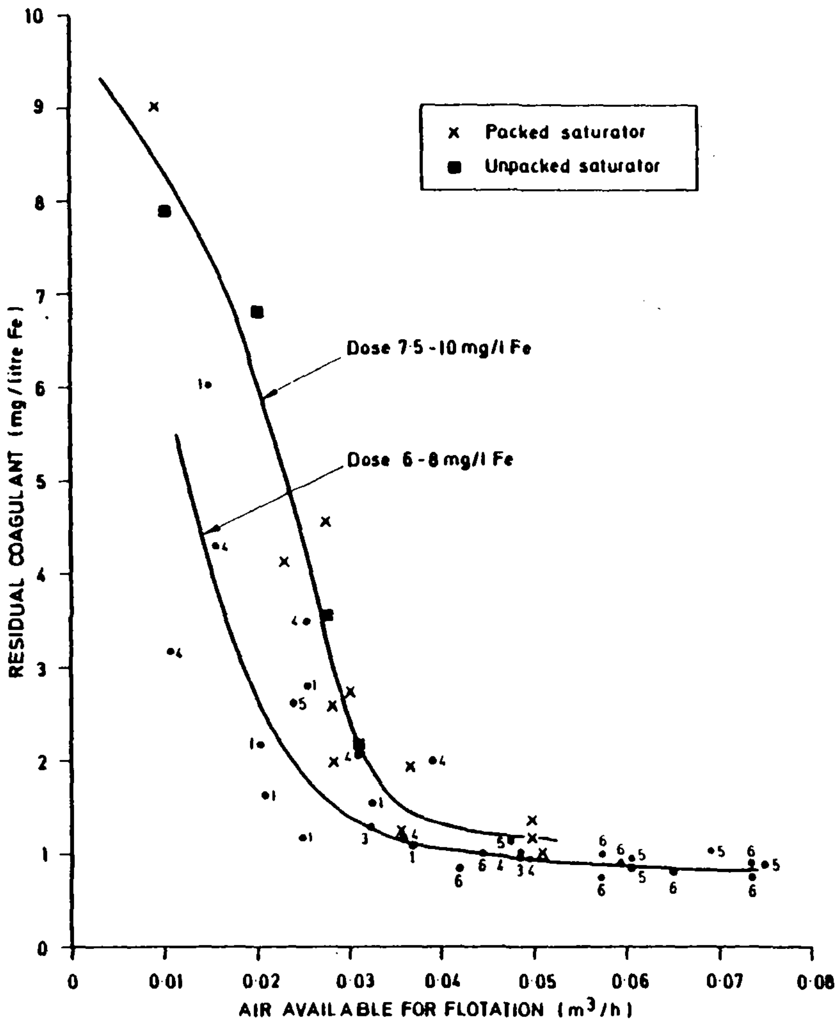

Figure 20. Effect of air available for flotation on residual coagulant (plant throughput 8.2 m³/h River Thames water)

Thus, provided optimum operating conditions were being employed, no change in treated water quality was observed over a throughput range 1.8 to 8.2 m^3/h. However in order to maintain a constant treated water quality during periods of high turbidity and colour in the raw water, it was found to be necessary to reduce the flow of flocculated water through the flotation tank from 8.2 to 6.8 m^3/h whilst maintaining the same flocculation and volumetric recycle rates (Table 5). The decrease in flow rate through the flotation tank resulted in increasing the retention time from 5.4 to 6.4 minutes. No benefit was gained from reducing the flow below 6.8 m^3/h through the flotation tank. Reducing the raw water flow throughout the whole plant to 6.8 m^3/h, thus increasing the flocculation time from 8.7 to 10.5 minutes, gave no further improvement in treated water quality (Table 5).

Table 5. Effect of throughput on treated water quality during periods of high raw water turbidity and colour

Flow through flocculator (m^3/h)	Flow through* flotation tank (m^3/h)	Coagulant concentration (mg/l Al)		Turbidity (FTU)	
		dosed	treated	raw	treated
8.2	8.77	5.56	2.2	55	23
8.2	7.37	6.3	0.79	45	3.0
8.2	6.02	5.79	0.84	58	5.4
8.2	4.21	5.97	0.71	63	4.1
8.2	2.87	5.14	0.72	56	4.4
6.8	7.37	6.35	0.92	44	4.7
2.3	2.87	7.8	0.61	56	3.7

* Includes 0.57 m^3/h of recycle water.

3.6. FLOTATION TANK INTERNAL ARRANGEMENT

When the plant was treating water at 8.2 m^3/h, it was found necessary to place the first baffle in the flotation tank closer than 0.25 m from the flocculated water velocity inlet (Figure 1) in order to prevent flotation in the downflow chamber. However, if the distance was made less than 0.10 m floc breakup occurred and this resulted in poor treated water quality. Thus the first baffle was located 0.2 m from the flocculated water inlet. Modifying the gap between the first baffle and the base of the tank from 0.1 to 0.3 m had no apparent effect on treated water quality. However, if the gap was increased to 0.75 m, or if the first baffle was removed altogether, poor mixing of flocculated and recycled water occurred and this resulted in a deterioration in treated water quality. The first baffle was therefore placed vertically 0.2 m from the flocculated water inlet with a 0.2 m gap between it and the base of the tank. The water velocity produced in the downflow section was 146 m/h.

The position of the second baffle was found to be less critical than the first provided the sludge was removed continuously. However, if sludge was allowed to accumulate on the water surface, a vertically-mounted baffle 0.2 m from the first baffle with a 0.3 m gap between the baffle and the water surface, resulted in water scouring the floated sludge.

Increasing the distance from the first baffle and the gap between the baffle and the water surface resulted in less scouring but also caused 'short circuiting' of unclarified water. Best results were obtained when the baffle was inclined at an angle of less than 45° to the vertical. Angles greater than 45° resulted in short circuiting.

The final position of the second baffle was such that at its base it was 0.2 m from the first baffle and at its top it was 0.4 m from both the first baffle and the water surface. The velocity in this section was reduced from 146 m/h at the base of the tank to 73 m/h as the water overflowed the baffle. The downflow velocity in the final section of the flotation tank was 16 m/h, leading to an average downflow for the whole of the flotation tank of 12 m/h. If either or both of these baffles were removed, short circuiting of unclarified water to the outlet occurred and resulted in poor treated water quality.

When the tank depth was halved from 1.2 m to 0.6 m (i.e. the water depth was decreased from 1.1 m to 0.5 m) very little separation of floc occurred and any floated sludge that was formed was immediately scoured from the water surface and carried through the clean water off-take. It was apparent from visual observation that insufficient time was being allowed for separation.

3.7. FILTRATION

Filtration was found to be a practical way of assessing the performance of the flotation unit. By comparing the performance of filters fed by flotation-treated water and upflow floc-blanket-clarified water, it became apparent that these waters had similar filtering characteristics, provided the treated water turbidities and residual coagulant concentrations were similar.

Examples of filtration at 2 mm/s (150 $g/h/ft^{2}$) of flotation-treated water and upflow, floc-blanket-clarified water on anthracite/sand filters are given in Figures 21 and 22 respectively. Both figures relate to the same date, raw water supply and similar coagulant doses.

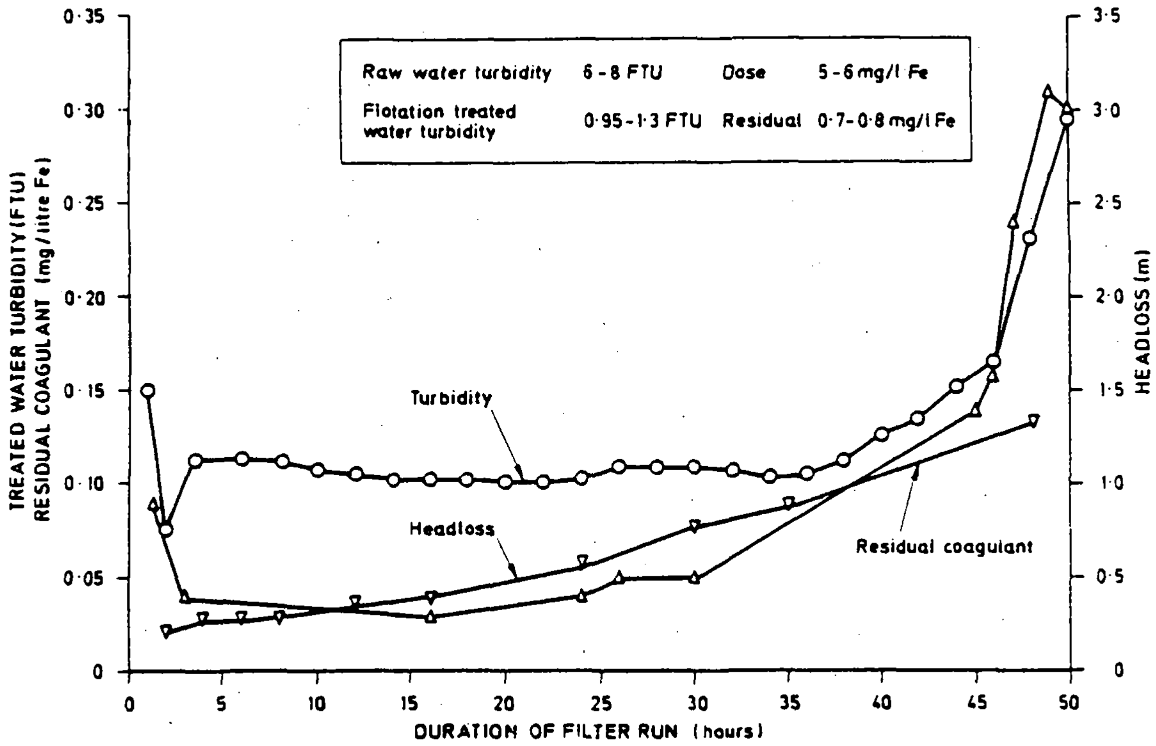

Figure 21. Filtration of flotation-treated water

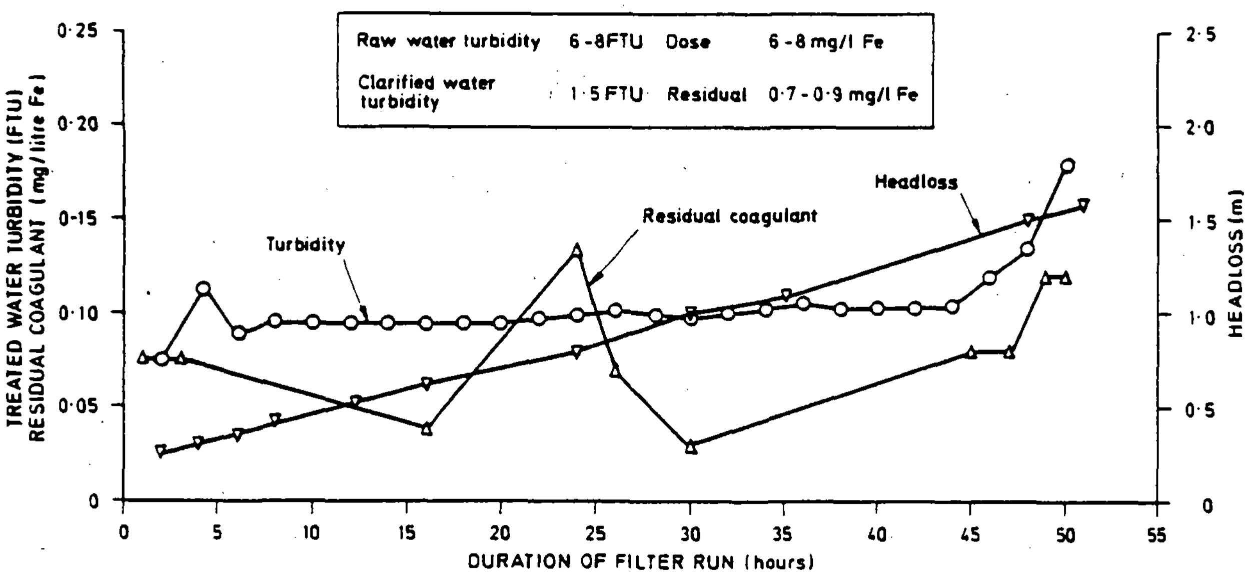

Figure 22. Filtration of upflow floc-blanket-clarified water

3.8. EFFECT OF SLUDGE REMOVAL ON WATER QUALITY

It was found that, provided the water level was maintained at the sludge off-take weir, sludge removal by continuous skimming did not disturb the treated water quality.

Similarly, the treated water quality remained constant if the sludge was allowed to accumulate undisturbed in the flotation tank for a period of up to 48 hours; longer periods of accumulation resulted in a gradual and steady increase in treated water turbidity (Figure 23).

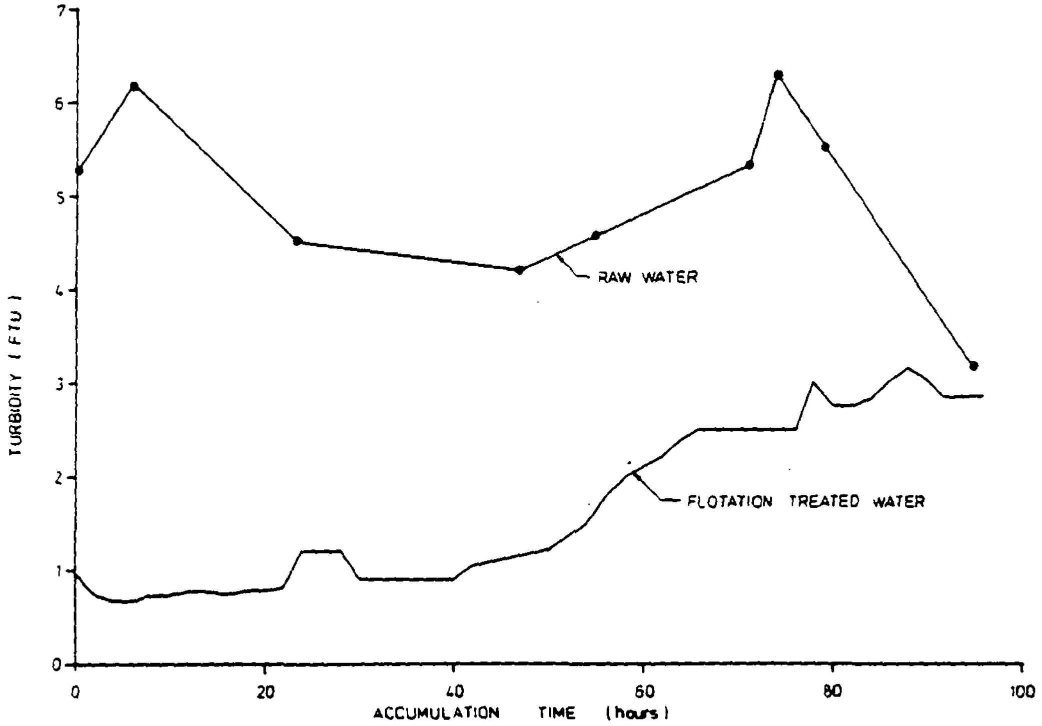

Figure 23. Effect of sludge accumulation on flotation-treated water turbidity

Intermittent sludge removal produced a constant water quality during the period of accumulation (provided the period was less than 48 hours) and a deterioration in quality during the period of, and for about 10 minutes after, the skim (Figure 24). The level of disturbance depended on the frequency and speed of skimming and on the length of skim. Least disturbance was caused when sludge was removed frequently, the skim being slow and of short duration. Short, slow, infrequent, skims produced a steady water quality but also a gradual accumulation of sludge on the water surface. The only combination of frequency and length of skim that kept a constant quantity of sludge on the water surface and gave a consistent water quality was continuous skimming, removing all of the sludge.

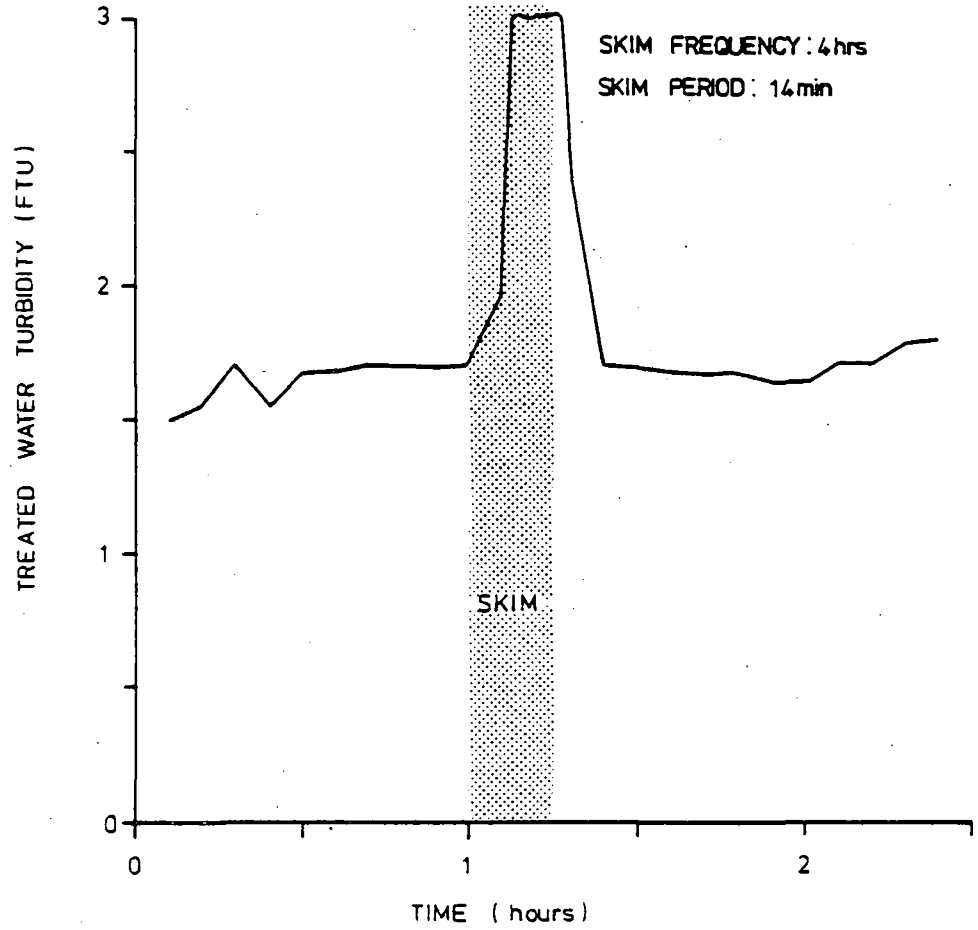

Figure 24. Effect of sludge removal on flotation-treated water turbidity

3.9. SLUDGE

The solids content of the sludge removed from the flotation tank was found to be independent of the coagulant used, but was influenced by raw water quality (3) and the period of accumulation on the water surface (Figure 25).

Sludge removed by continuous skimming was in the order of 1 to $2\frac{1}{2}\%$ dried solids; intermittent skimming increased the sludge concentration to 6 to 8% if removed every 24 hours. Sludge concentrations of 12 to 14% dried solids were recorded when accumulation has been allowed to take place for 24 hours and the raw water turbidity was 100 FTU.

A comparison of sludges produced by flotation and by floc blanket clarification demonstrated that they had similar settling and thickening properties when subjected to thorough slow stirring. However, if flotation-produced sludge was not stirred or subjected to shear when removed from the flotation tank it would float and thicken.

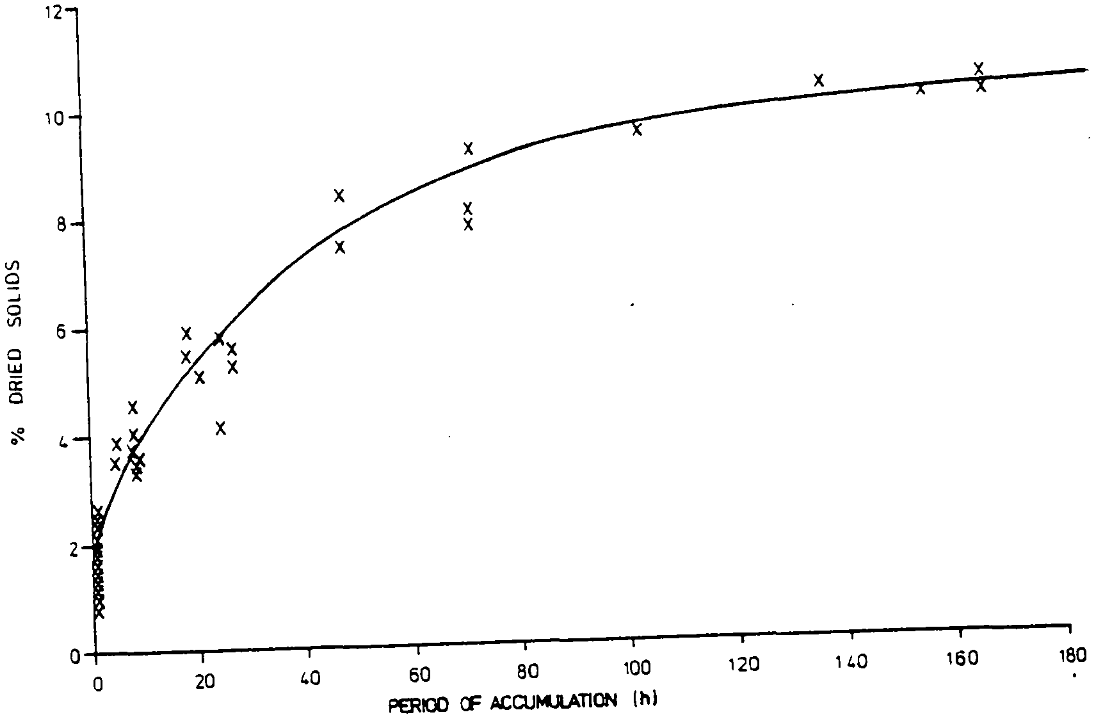

Figure 25. Effect of period of accumulation on sludge concentration

4. DISCUSSION

The work carried out on this 8.2 m^3/h flotation pilot plant has, in general, confirmed the previous WRC findings. There are, however, a number of points that were not apparent from the earlier work.

Flotation was found to be a much more rapid process than sedimentation. Under most raw water conditions it was possible to operate the plant with 1½ minutes flash mixing, 9 minutes flocculation and 5½ minutes flotation, without causing a deterioration in treated water quality. However, under the conditions of high turbidity and colour which are experienced on the River Thames for short periods each year it was necessary to increase the flotation time to 6½ minutes in order to maintain treated water quality. Because of the rapidity of the process, a steady treated water quality was produced within 45 minutes of start-up. Similarly, the full effect of a change of operating conditions was seen in the treated water quality within 20 to 30 minutes.

The water quality produced by four-stage tapered mechanical flocculation followed by flotation was comparable with that produced by an efficiently run upflow floc blanket clarifier. Under conditions of high turbidity and colour, water produced by the settling process tended to be better than that from flotation, but under low turbidity conditions and during algal blooms the reverse was true. However, it was felt that given more operating experience with high turbidity waters the performance of the flotation plant could be further improved.

For clarification of River Thames water by flotation, the optimum volume of water to be saturated with air at 345 kPa and recycled was 6 to 8% of the volume of water to be treated. However, it was found that if 8% recycle was exceeded a deterioration in treated water quality could occur. This was probably due to floc breakdown as the turbulence at the point of dissolved air introduction increased with increasing percentage recycle. There was a noticeable deterioration when raw water turbidity, colour and coagulant dose were high; under these conditions, the floc produced was weaker and more readily broken down.

It was found inadvisable to control the recycle flow rate by a valve upstream of the WRC nozzle because the pressure drop that occurred across the valve caused premature deaeration of the recycled water. This led to bubble coalescence and an inability of the comparatively large bubbles to attach themselves to the floc. This, in turn, resulted in a deterioration in treated water quality. A second factor that may have led to poor treated water was the increased turbulence and possible floc breakdown that occurred as a result of the higher rise rate of the larger bubbles.

In Section 3.4. it was shown that if poor flotation resulted because of inadequate dissolved-air, this could be overcome by increasing the saturator pressure and thus increasing the volume of air available for flotation. This could be of major importance if the floc produced was being broken down by turbulence at the point of dissolved-air injection. An effective method of overcoming the problem may be to reduce the recycle flow rate to minimize the turbulence and to increase the saturator pressure sufficiently to maintain the volume of air available for flotation.

It is a well established chemical engineering fact that in absorption when the main resistance to mass transfer occurs in the liquid phase (as it does in an air/water system) the most efficient system is a packed column with a large surface area/volume ratio. A spray tower (unpacked column) is comparatively inefficient. The work described in Section 3.4. showed that, when using an unpacked column for dissolving air in the recycle stream, a higher pressure was required in order to produce a similar treated water quality.

In terms of treated water quality, the optimum volume flow rate of air required when treating 8.2 m^3/h of River Thames water was 0.03 to 0.05 m^3/h, (i.e. 3.7 to 6.1 litres air/m^3 water was required for efficient treatment). The fact that this optimum was independent of percentage recycle, saturator pressure and whether a packed or unpacked saturator was used, indicated that volume of air/volume of water to be treated was the important parameter. This optimum air requirement was found to be independent of raw water turbidity; however, it was felt that treatment of waters with higher turbidities than those found during the course of these experiments may require a larger air/water ratio.

As in previous work it was found that laboratory sedimentation jar testing could be used to predict the optimum dose for dissolved-air flotation. The deterioration in treated water quality that occurred if the optimum dose was exceeded (Section 3.2.) was due to the production of a weaker floc at high coagulant doses and its breakdown at the point of air injection in the flotation system.

Sludge produced by flotation varied between 1 and 14% solids depending on raw water quality and frequency of sludge removal. It became apparent that further investigations into methods of sludge removal using the present pilot plant would not be relevant to larger plant. Accumulated sludge adhered to the walls of the flotation tank and when disturbed by the action of the skimmer a small proportion sank and was carried over to the filters. On a larger scale of flotation tank this wall effect should be proportionately less. Furthermore, whereas it was found necessary to use a skimmer to remove the float on this 8.2 m^3/h flotation pilot plant, it may be found that sludge will freely flow over a sludge off-take weir on a larger scale where the wall effects will be considerably reduced.

One of the factors greatly influencing flotation-treated water quality and filter performance was flocculation. Work carried out confirmed earlier WRC work (3), that, in order to achieve a good treated water quality in terms of turbidity and residual coagulant it was necessary to have adequate pre-flocculation. In order to flocculate the water sufficiently, it was found that three or four stages of flocculation were needed. Poor treated water quality occurred as a result of inadequate flocculation if the paddle speeds, and thus the power input, were low. It was found for this plant, treating River Thames water, that a power input equivalent to that produced by uniform flocculation at 30 to 40 rev/min was required for adequate flocculation. The ratio of the paddle speeds was found to be of paramount importance in producing a good treated water quality. If the ratios of the paddle speeds were large (e.g. 27:9: 3:1) inadequate flocculation and poor treated water quality resulted. An improvement in treated water quality occurred when uniform flocculation was modified to slightly tapered flocculation (paddle speed ratios 1.6 : 1.45 : 1.25 : 1). This confirmed the findings of an earlier WRC report (15) which states that the requirement for optimum floc formation is a reduction in shear rate as the floc size builds up.

Inadequate flocculation resulted if the ratio of paddle speeds was large because the energy input into the final stages was insufficient to continue the flocculation process. However, if uniform flocculation was used, the paddle speed in the final stages of flocculation was such that the shear broke down the floc already produced.

5. CONCLUSIONS

5.1.

Adequate flocculation was an essential requirement for efficient flotation. The best method of flocculation was found to be slightly tapered four-stage mechanical flocculation, but further research needs to be carried out to optimize this stage of the process.

5.2.

For good clarification, it was necessary to recycle 6 to 8% of the treated water saturated with air at 345 kPa (50 psig) into the flocculated stream. At higher pressures lower volumes of recycle could be used. The optimum volume of air available for flotation, in terms of treated water quality, was found to be 3.7 to 6.1 litres air/m^3 Thames water.

5.3.

The flow of recycled water and the liberation of dissolved air could be satisfactorily controlled using a nozzle which was developed for this purpose. If the flow was controlled by a valve upstream of the nozzle, the pressure drop across the valve was sufficient to make air come out of solution before the nozzle. This led to bubble coalescence and resulted in a deterioration in treated water quality.

5.4.

If an unpacked saturator was used instead of a packed saturator an increase in pressure of 100 to 200 kPa was required in order to achieve a similar water quality.

5.5.

Sedimentation jar testing could be used to predict the optimum coagulant dose for flotation, but overdosing could lead to poor treated water quality.

5.6.

The internal arrangements of the flotation tank were flexible, but care had to be taken not to cause areas of high shear which could result in floc breakdown.

5.7.

A steady water quality was achieved within 45 minutes of start-up and the response to alterations in operating conditions was rapid (20 to 30 minutes).

5.8.

In order to achieve constant treated water quality over a wide range of raw water conditions, the retention times in the flash mixer, flocculator and flotation tank were $1\frac{1}{2}$, 9, and $6\frac{1}{2}$ minutes respectively. The latter could be reduced to $5\frac{1}{2}$ minutes for the majority of the time.

5.9.

Provided the optimum coagulant dose, pH, recycle rate and raw water throughput were employed, flotation treatment of Thames water produced a treated water quality comparable with that of an efficiently operated, upflow floc blanket clarifier.

5.10.

Flotation was a more efficient process than upflow floc blanket clarification for the removal of small centric diatoms from River Thames water.

5.11.

Provided treated water turbidity and residual coagulant concentrations were similar, flotation-treated and upflow floc-blanket-clarified waters had similar filtering characteristics.

5.12.

It was found necessary to use a mechanical skimming device to remove sludge. Intermittent skimming produced a 'dry' sludge and a deterioration in treated water quality for the period of removal. Continuous skimming resulted in lower sludge concentrations, but no deterioration in treated water quality. Further investigations of sludge removal methods will be more appropriate on a larger-scale plant.

5.13.

Sludge concentrations produced by flotation were far higher than those from upflow floc blanket clarifiers and could be 1 to 14% depending on raw water quality and removal methods.

5.14.

Further investigations are required to obtain operating experience with different types of waters.

APPENDIX A. FLOCCULATOR POWER REQUIREMENT

Experimental work was carried out in order to determine the relationship between paddle speed and power input for the paddles described in Section 2.3.1.

The torques required to turn the paddle through water over the range of speeds used were measured and are summarized below:

Paddle speed (rev/min)	Torque (Joule)
20	0.32
40	0.64
57	1.13

Figure 26 shows that for the speed range used, torque was proportional to the square of the paddle speed.

i.e. torque $\propto$ (rev/min)^2

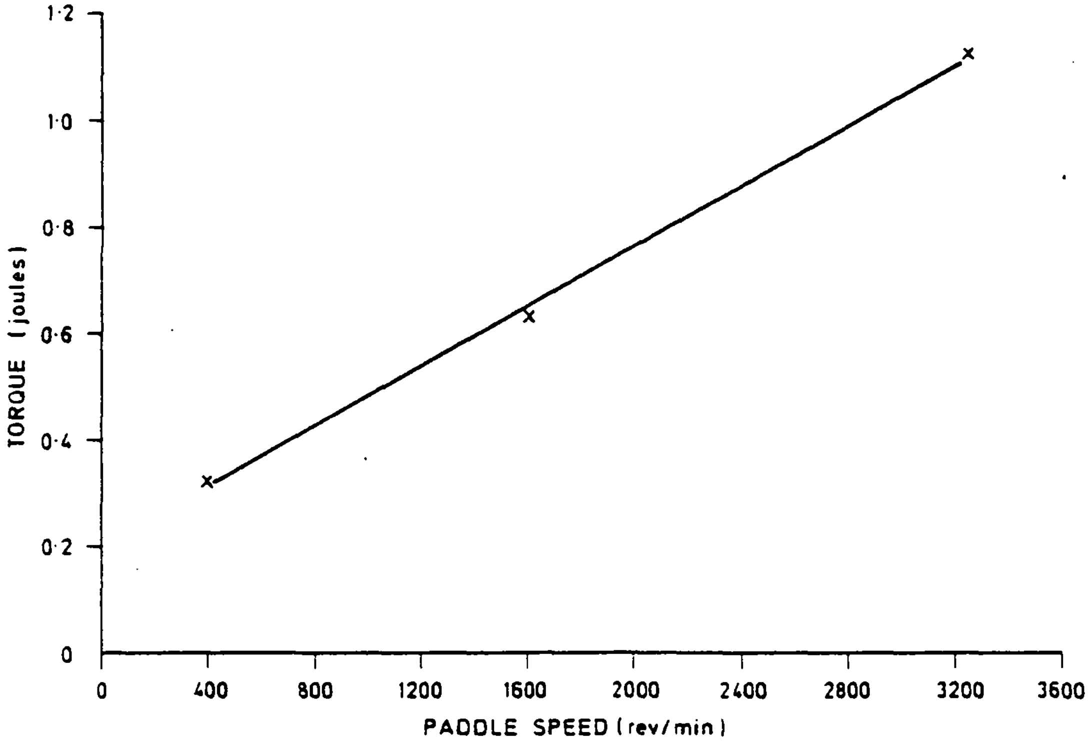

Figure 26. Torque as a function of the square of the paddle speed

For a given system, the mechanical power developed is proportional to the product of the torque and the paddle speed (16).

$$\text{i.e. power} \propto \text{torque} \times \text{rev/min}$$
$$\therefore \quad \text{power} \propto (\text{rev/min})^3$$

Thus the power put into the flocculator, with the paddles described in Section 2.3.1. over the speed range 20 to 57 rev/min, was proportional to the sum of the cubes of the paddle speeds.

Table 6 summarizes the paddle speeds used at each energy level and paddle speed ratio.

Table 6. Flocculator paddle speeds at the three discrete energy input levels

Paddle speed (ratio)	Flocculator paddle speeds (rev/min)											
	Stages				Stages				Stages			
	1	2	3	4	1	2	3	4	1	2	3	4
1 : 1 : 1 : 1	20	20	20	20	30	30	30	30	40	40	40	40
1.6 : 1.45 : 1.25 : 1	23.5	21	18.5	14.5	35	32	28	22	47	42.5	37	29.5
2 : 1.6 : 1.25 : 1	26	20.5	16	13	38.5	30.5	24.5	19.5	51.5	41	32.5	25.5
3 : 2.1 : 1.45 : 1	-	-	-	-	42	29	20	14	55.5	39	27	18.5
4 : 3 : 2 : 1	27.5	20.5	13.5	6.75	41	30.5	20.5	10.5	54.5	41.5	27.5	14
8 : 4 : 2 : 1	30.5	15	7.5	3.75	45.5	23	11.5	5.5	60.5	31	15.5	7.5
27 : 9 : 3 : 1	31.5	10.5	3.5	1.25	47	16	5.5	1.75	62.5	22.5	7.5	2.5

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