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Final Report

THE EFFECTIVENESS OF SWIMMING POOL FILTRATION FOR THE REMOVAL OF CRYPTOSPORIDIUM OOCYSTS

FOR

THE POOL WATER TREATMENT ADVISORY GROUP (PWTAG)

July 31st 2010

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SUMMARY

- *Initial work (Report to PWTAG by WQM Ltd and Swansea University, "Simulated Cryptosporidium removal under swimming pool filtration conditions", Nov 21st 2004) showed that surrogate particles of a similar size to Cryptosporidium oocysts were poorly removed under swimming pool filtration conditions (flow rate 25m/hr) without coagulant for a single pass through the filter.*
- *With coagulant addition better than 99% removal could be obtained but only with higher coagulant doses than the minima recommended by PWTAG.*
- *In order to determine whether the surrogate particles behaved similarly to live oocysts a small pilot plant was constructed which could be contained in a Class 2 biological containment cabinet and all parts and water samples decontaminated. It was not possible to use real oocysts on the large pilot plant used previously due to the biological hazard.*
- *It was shown that the small pilot plant gave similar removals of surrogate particles to the large pilot plant both with and without coagulants.*
- *Using the small pilot plant, it was shown that live oocysts are better removed when coagulant is used. However, removals were better than for surrogate particles, particularly without coagulant (90% as opposed to <50% for surrogate particles). The much lower concentration of oocysts compared to surrogate particles may have influenced these results.*
- *Due to health and safety concerns at the University inactivated oocysts were also investigated. These were much better removed than surrogate particles and live oocysts without coagulant (99.5%) in the limited number of experiments performed . Again the low concentration of oocysts may have influenced the results but inactivated oocysts were not considered further.*
- *The relative concentrations of surrogate particles and oocysts were dictated by the materials available and their analytical methods. Attempts to lower the detection limits of the in-house method for surrogate particles did not give a practically useful technique.*
- *All pilot plant runs to this point had been performed using tap water modified to simulate pool water. In order to investigate the effects of using real pool water the large pilot plant was moved to the Welsh National Pool at Swansea.*
- *Surrogate particle removal from real pool water under either high or low bathing load was not considered to be different from modified tapwater.*

- *Due to problems of supply of filter sand, crushed glass filtration media were being introduced for pool water treatment. Two of these glass filter media were investigated using the large pilot plant at the Welsh National Pool and were not found to behave differently from filter sand for the removal of surrogate particles.*
- *All the above experiments were performed with clean filter media. In order to investigate the effects of accumulated debris on surrogate particle removal the pilot plant was modified to run continuously on pool water.*
- *Surrogate particles were added on Days 1, 3 and 5 of 5 day continuous filtration runs with and without coagulant.*
- *Over 5 days filter headloss was not excessive with PAC addition at 0.05mgAl/l.*
- *Surrogate particle removal improved during 5 day continuous filtration runs both with and without coagulant.*

CONTENTS

THE POOL WATER TREATMENT ADVISORY GROUP (PWTAG)

THE EFFECTIVENESS OF HIGH RATE FILTRATION FOR POOL WATER TREATMENT

1. INTRODUCTION

a) Initial bench and pilot plant work using polystyrene beads of a similar size to Cryptosporidium oocysts showed that removal from modified tap water under swimming pool filtration conditions (sand filter 600mm deep operated at 25m/h) was less than 50% for a single pass through the filter without the use of coagulants.

b) With the use of coagulants better than 99% removal could be obtained (Report to PWTAG by WQM Ltd and Swansea University, "Simulated Cryptosporidium removal under swimming pool filtration conditions", Nov 21st 2004)

c) In order to verify the suitability of the surrogate particles and to obtain results under conditions closer to those of full size swimming pools, the following points needed to be addressed :-

- A comparison of single pass filtration efficiency using surrogate particles and real Cryptosporidium oocysts.
- Determination of the effects of using real swimming pool water rather than modified tap water.
- Determination of the effects of different water qualities on removal efficiencies.
- Determination of the effects of the build up of material on the filter media during a long filter run on removal efficiencies.

d) In order to carry out the further experimental work PWTAG agreed provide part of the funding to support a series of MRes students at Swansea University. The agreed experimental programme is appended (Appendix 1).

e) This programme was subsequently modified as below :-

- Carry out a study of AFM crushed glass filtration media in year 2, rather than investigating different filter bed depths.
- Investigation of the effects of the build up of material on the filter media in year 3.
- Year 4 was not funded.

f) The work was supervised by Dr Christopher Wright, Dr Colin Hayes, Dr Brian Croll and latterly Dr Robert Keirle

g) The Students who carried out the work were David Rowlands, Harriet Henley, Camille Anex and Tanya Liebrick

2. LITERATURE SURVEY

a) A literature survey was made by each student at the beginning of their project period, no new information was revealed with the exception of the work of Dr James Amburgey at the University of N Carolina at Charlotteville discovered in late 2008.
b) Dr Amburgey was also carrying out work on the removal of Cryptosporidium oocysts during pool water treatment and contact and liason with him were established.

3. THE LARGE PILOT PLANT

a) A diagram of the pilot plant is given in Fig 1 and a photograph in Fig 2. There is provision to recirculate the water in the feed tank T1 back to T1after filtration or to route the filtered water to the filtered water tank T2.
b) The filter can be backwashed using water from T1. The valve positions for the modes of operation are given in Appendix 2 together with the order of opening/closing.
c) The heater circuit is also used to mix the contents of T1. A by-pass loop around the mixing pump P1 allows the rate of mixing to be varied using valve V21.
d) Pipework is largely constructed in 25mm internal diameter grey UPVC and the filter column in 150mm i.d. clear (translucent) UPVC. The initial filter bed consisted of 600mm of 16/30 mesh (approx 0.65 mm mean particle diameter) filter sand supported on 300mm of gravel (about 2 to 20mm diam.).
e) The flowmeter and dosing pump were calibrated before experimentation was begun by each student operating the plant.
f) During filtration flows were controlled by the combined usage of the membrane valves V5 and V6 and during backwash by the membrane valves V5 and V11.
g) Filtration flow was typically 450 or 900 l/hr (25 or 50 m/hr filter downflow) and during backwash such as to give 25% bed expansion (about 1100 l/hr). More detailed operating procedures are given in Appendix 2.
h) A typical operating sequence at 25 m/hr downflow rate was :-

    i) Fill T1 with tap water and bring up to 30^{O}C.
    ii) Adjust the free chlorine to about 1.5 mg/l using sodium hypochlorite, and the alkalinity to about 120 mg/l as calcium carbonate using sodium bicarbonate and calcium chloride. (calcium chloride was added as in practice alkalinity would be naturally present as calcium bicarbonate). Adjust pH to 7.2 to 7.5.
    iii) Backwash filter for 5min. then return to filtration with recirculation to T1
    iv) Run for 30 min to ripen filter.
    v) Add surrogate and run for a further 10 min in recirculation mode to ensure that the volume of water above the sand filter contains water with particles.
    vi) Switch filtrate to T2 and run for 60 min., collect samples of T1 and filtrate.
    vii) Return filtrate to T1
    vii) Drain T2 and refill T1.

Fig 1. Diagram of Pilot Plant

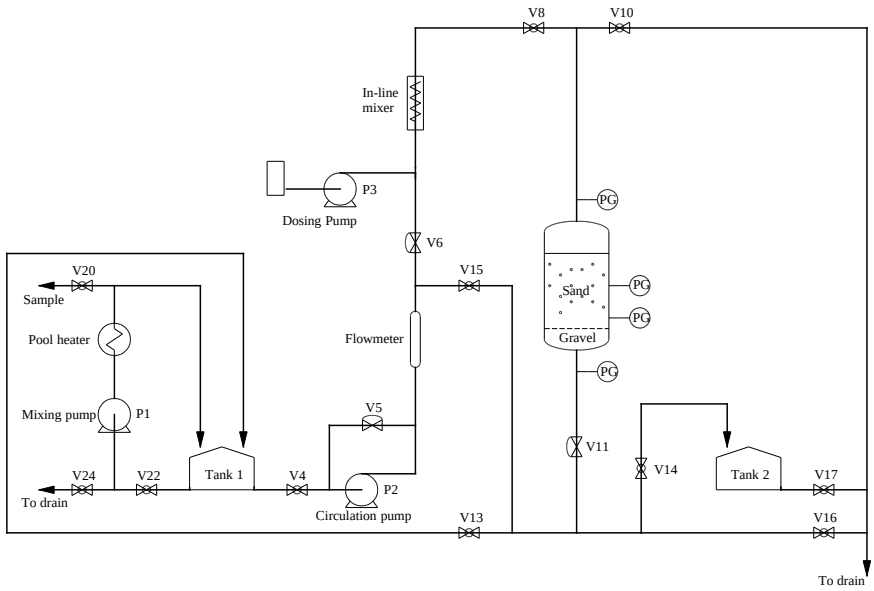


Fig 2. Photograph of Large Pilot Plant

4. THE SMALL PILOT PLANT

a) Cryptosporidium is a Class 2 pathogen (pathogenic organism with no effective treatment available) and must therefore be contained securely. This means no unauthorised entry into the area of use, secure facilities, ventilation drawn out of the area and the exit air filtered through a filter capable of filtering out all the pathogenic organisms, etc..
b) In the context of a teaching University it was not possible to provide the necessary facilities to house the large pilot plant.
c) It was therefore decided to build a scaled down version of the pilot plant which would fit into a large Class 2 biological cabinet which was available in the microbiology department. This cabinet was already in a secure laboratory with restricted access.
d) Facilities had to be provided to disinfect all parts of the pilot plant and any liquids used or produced within the cabinet.
e) To avoid scale-down effects in pilot plant filters the diameter of the filter must be at least 30 times the diameter of the filter media. For 0.65mm sand particles this means a minimum filter diameter of 19.5 mm.
f) A 50mm diam filter was decided upon as this was larger than the minimum and at 25m/hr downflow rate gave a filtered volume of about 10 litres in an hour. 10 litre vessels could be accommodated in the Class 2 cabinet and disinfected without too much trouble. This meant that the large pilot plant run conditions could be mimicked using the small pilot plant.

g) The flow diagram of the small pilot plant is as shown in Fig 1, except that T1 was mixed with a stirrer, rather than water recirculation using a pump and the water heater was submerged in T1.
h) All parts were constructed as far as possible in stainless steel.
i) A photograph of the plant is given in Fig 3.

5. SURROGATE PARTICLES

The Cryptosporidium surrogate particles were purchased from Environmental Tracing Systems Ltd (ETS). These consisted of polystyrene beads of 2 to 7μm quoted diam. The particle size range was confirmed by measurements at Swansea University. The beads were stained with a fluorescent marker in order to ease identification in water samples and to aid their counting.

6. CRYPTOSPORIDIUM OOCYSTS

Cryptosporidium oocyst suspensions were supplied by

7. ANALYSIS

a) Equipment for the analysis of free chlorine, turbidity and pH were kindly loaned by Tintometer Ltd.
b) In the initial work, analysis of water samples for numbers of surrogate particles was carried out by ETS, this was too expensive for the funding level of the MRes programme and a method of analysis was developed for in house use by the M Res students. An outline of the method is given in Appendix 3.
c) 100ml samples of T1 (the feed tank to the pilot filter) and T2 (the filtered water) were taken every 10 mins during 60 min runs (25m/hr) or every 5 mins during 30 min runs (50m/hr). These samples were combined to give a 600ml composite sample of each of T1 and T2.
d) Analysis for aluminium was performed by Corus Ltd using plasma emission spectroscopy.
e) Analysis for Cryptosporidium oocysts was carried out by The NPHS UK Cryptosporidium Reference Unit, Singleton Park, Swansea.

Fig 3. Photograph of Small Pilot Plant

8. SURROGATE PARTICLE REMOVAL USING THE SMALL PILOT PLANT

a) In order to show that the small pilot plant had similar performance to the large pilot plant, the small pilot plant was operated with modified tap water using the

same surrogate particle concentrations as the large pilot plant, both with and without coagulant.

b) The results, compared to the large pilot plant are summarised in Table 1

c) It will be seen from Table 1 that the performance of the two pilot plants is similar in that less than 40% surrogate removal is experienced at zero coagulant addition, whereas better than 90% removal is shown at a PAC dose of 0.05 mgAl/l

d) At zero coagulant addition the large pilot plant had one anomalously low oocyst removal which may have biased the results and it is felt that performance at zero coagulant dose is closer than the figures indicate.

e) The conclusion is that the two pilot plants behaved similarly for the removal of surrogate particles

Table 1. Comparison of the large and small pilot plant performances

Coagulant Dose PAC mgAl/l	Small Pilot Plant		Large Pilot Plant	
	No of Experiments	% Surrogate Removal Small Pilot plant	No of Experiments	% Surrogate Removal Large Pilot plant
0	**4**	**34.7**	**3**	**22.0**
0.05	**4**	**90.4**	**2**	**94.4**

9. CRYPTOSPORIDIUM OOCYST REMOVAL USING THE SMALL PILOT PLANT

a) The small pilot plant has been used with sand media and a filtration rate of 25 m/h for both live and inactivated oocysts.

b) The use of inactivated oocysts was not included in the initial work programme as they were suspected to have different surface properties than live oocysts. Health and safety considerations at the University dictated that for part of the time allotted to this work it was not possible to use live oocysts and therefore inactivated oocysts were used.

c) In both cases, the loading of oocysts onto the filter was much lower than that of surrogate particles, in the range 25 to 38 per ml compared to 50,000 to 80,000 per ml for surrogate particles. The results are summarised in Table 2.

d) Again, the results demonstrate the benefit of dosing coagulant. However, the difference between filtration with and without coagulant addition is much less pronounced at the considerably lower oocysts loadings that were applied.

e) For live oocysts there is a definite benefit of adding coagulant although removal without coagulant is much better than for surrogate particles. The much lower number of particles per ml used for oocysts compared to surrogate particles may have influenced these results

f) For inactivated oocysts there is effectively no difference in removal with or without coagulant. Again the low number of oocysts per ml may have influenced the results.

g) The results show that the surrogate particle removals probably underestimate the removal of oocysts by sand filtration, giving an added safety factor to treatment systems based on surrogate particle removal
h) The low numbers of oocysts added in the small pilot plant experiments were dictated by the purified suspension available and it's matrix. Adding large numbers of oocysts per ml would have added sufficient matrix to distort the coagulation results.
i) The high numbers of surrogate particles per ml were dictated by the limits of detection of the analytical method used to enumerate them.
j) The possibility of lowering the detection limit for surrogate particles was investigated. The experiments were based on concentrating the final sample volume well below the 10ml being used. This was possible as only 25µl are needed for the haematometer cell.
k) Further concentration of the 10ml sample using smaller membrane filters and centrifugation was investigated and showed some promise but it was not adopted routinely due to the lengthy time needed for each analysis.
l) The use of centrifugation to concentrate directly from the 600ml sample was not possible due to the lack of availability of suitable equipment at the university.
m) Similar methods to those used for oocyst enumeration should give better limits of detection than the in-house method but the high costs would have severely restricted the amount of work possible

Table 2. Sand filtration of live and inactivated *Cryptosporidium oocysts*

(a) Live oocysts

Number of runs	Nominal PAC dose mg/l (Al)	Oocysts per ml filter inlet	Oocysts per ml filter outlet	Average % Removal
6	0	25	1.513 to 3.870	89.6
6	0.05	25	0.003 to 0.008	99.9

(b) Inactivated oocysts

Number of runs	Nominal PAC dose mg/l (Al)	Oocysts per ml filter inlet	Oocysts per ml filter outlet	Average % Removal
2	0	33.4 to 38.0	0.137 to 0.201	99.5
2	0.05	26.6 to 33.4	0.016 to 0.031	99.9

10. LARGE PILOT PLANT RELOCATION TO THE WELSH NATIONAL POOL

a) The Pilot plant was dismantled and rebuilt in the treatment plant room at the pool.
b) A feed pipe from the input to the training pool filter was provided from which to fill T1. This was chosen rather than the feed to the main pool filters due to it's higher bathing load.

c) Runs were performed as in section 3h) except that the tank was filled with pool water immediately before a run and no adjustments to the water temperature or quality were made.
d) On-site measurements over several days showed that the pool continuous monitoring equipment and manual testing could be relied on for water quality data.

Fig 4. Photograph of Large Pilot Plant Installed at The Welsh National Pool, Swansea

11. LARGE PILOT PLANT RESULTS USING POOL WATER

a) Runs were made at periods of high and low bathing loads and with and without coagulant at 25m/hr.
b) The results are summarised in Table 3, together with a summary of the previous results using modified tapwater.
c) It will be seen that the use of pool water at either low or high bather loads makes little difference to the results and it is thought that they are probably not significantly different.

Table 3. Sand filtration results using the large pilot plant and real pool water

Bather Load	Coagulant Dose PAC mg(Al)/l	Mean % Removal	Mean % Removal with Modified Tap water
Low	0	**43.0**	**43.0***
High	0	**30.7**	
Low	0.05	**98.0**	**94.4**
High	0.05	**99.1**	

*One very low result eliminated as an outlier

12. COMPARISON OF SAND AND CRUSHED GLASS FILTER MEDIA

Table 4. Comparison of sand and AFM glass filtration media

	% Removal of Surrogate Particles							
	25m/h				50m/h			
	Sand		Glass		Sand		Glass	
Coagulant	**Runs**	**Mean**	**Runs**	**Mean**	**Runs**	**Mean**	**Runs**	**Mean**
None	61,90	**55.9**	34,20	**52.7**	74,40	**68.5**	32,10	**45.2**
	50,00		64,60		62,50		58,30	
			59,20					
PAC 0.05mg/l (Al)	93,20	**92.5**	92,00	**93.5**	89,50	**92.7**	86,60	**85.8**
	97,10		94,80		95,90		84,94*	
	87,22		93,80					

PAC 0.005mg/l (Al)	95,20	**91.1**	89,30	**83.9**	80,00	**76.8**	77,81*	**76.3**
	87,00		80,10		73,50		74,74*	
			82,30					
Alum 0.01mg/l (Al)	91,50	**92.9**	64,80	**75.9**	93,70	**80.0**	63,00*	**76.8**
	94,20		80,70		66,30		90,52*	
			82,10					

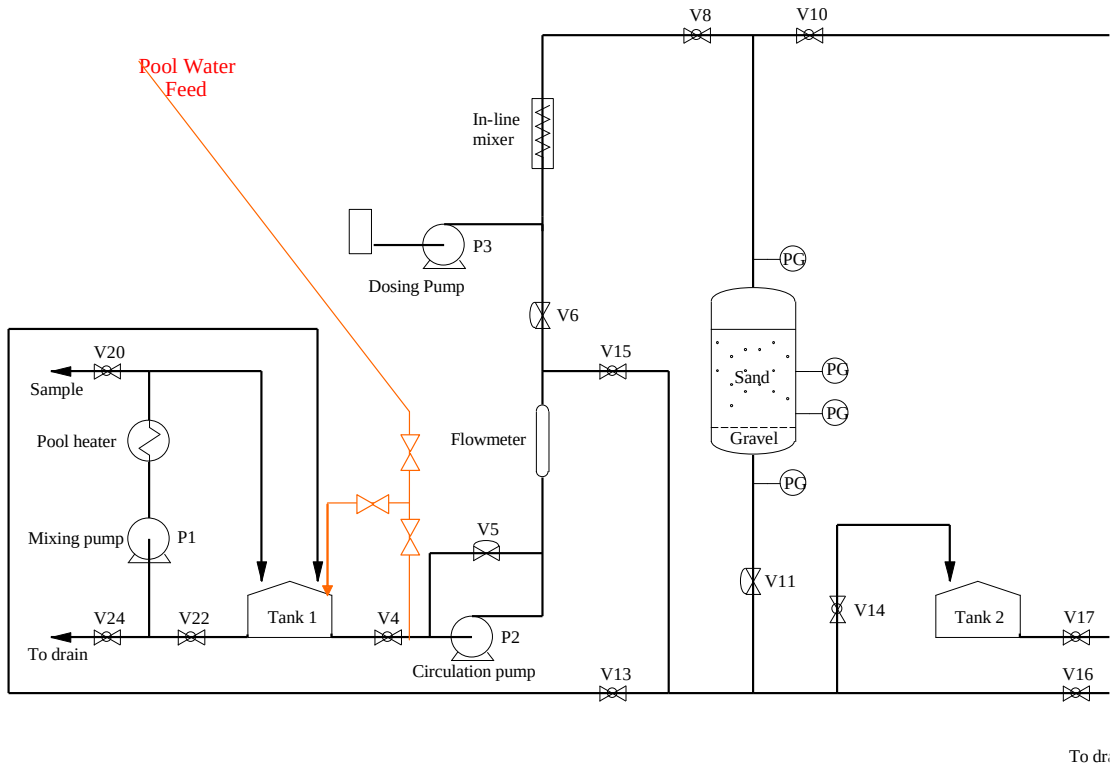
a) The large pilot plant was operated with pool water using both sand and crushed glass media with and without coagulant at 25 and 50m/hr.
b) The results for AFM glass media are summarised in Table 4 and for DMS glass media in Table 5.
c) The results show some apparent differences in performance of the media under specific operating conditions, however the overall conclusion is that there is probably no significant difference between them.
d) Again the benefits of using coagulants was demonstrated.

Table 5. Comparison of sand and DMS glass filtration media

Nominal PAC dose mg/l (Al)	% Particle removal by sand	% Particle removal by DMS glass media
0	29	34
0.005	63	43
0.05	94	99

13. LARGE PILOT PLANT OPERATION WITH A CONTINUOUS FEED OF POOL WATER

Fig 5. Modifications to the Large Pilot Plant to run continuously on Pool Water



a) All the work in previous sections of this report involved filtration of particles using a clean filter bed.
b) In order to investigate the effects of the build-up of material on the filter on surrogate particle removal, the pilot plant was modified to run with a continuous feed of pool water. The modifications are illustrated in Fig 5 to accommodate the experimental design in c) below.
c) The outline experimental design when adding surrogate particles was :-
    a. Operate the filter continuously for 5 days on pool water with and without coagulant. Measure the filter headloss.
    b. On day 1 at the beginning of the run, fill T1 with pool water and backwash the filter.
    c. Then refill tank 1 with pool water whilst operating the filter with pool water at the chosen flow rate.
    d. Switch on the T1 recirculation pump and add the surrogate particles to T1.
    e. Switch from running directly on pool water to running on T1.
    f. Take samples of T1 and filtrate every 10 min at 25m/hr flow or 5min at 50m/hr
    g. After 1hr (25m/hr) or 30min (50m/hr) switch back to running directly on pool water.
    h. Repeat c to g above on days 3 and 5
d) At the beginning of the study period, before the pilot plant modifications, the student ran the filter at different coagulant doses in batch mode (as previously) in order to check that they were obtaining results similar to previous students. The filter had AFM glass media during these experiments, which was changed to sand before the 5 day continuous flow experiments were begun. The results

are shown in Table 6 and were performed at 50m/hr. They show very good consistency with previous results.

e) In order to determine that the headloss build-up on the filters would not be excessive over a 5 day period the filter was operated continuously for 7 days without coagulant and the headloss measured. 50 m/hr flow was chosen to maximise fowling effects. This was performed for both AFM and sand. The results are shown in Table 7 and were similar for the two media. They showed that 5 day continuous runs were possible.

f) Continuous 5 day experiments were then run in triplicate for PAC coagulant doses of 0, 0.005 and 0.05 mgAl/l. The results are shown in Table 8. It will be seen that :-

   a. Headloss build-up through the runs was observed, this was higher at the higher coagulant dose. However the build up was not as great as had been expected.
   b. Particle removals were similar to batch experiments. Mean removals are compared in Table 9.
   c. In all but one run particle removal increased with filter fowling
   d. There was no evidence of filter breakthrough in 5 days

Table 6. Batch mode pilot plant results compared to previously

Run No.	Coagulant Dose mg(Al)/l	Particle count Tank 1	Particle count Tank 2	% Particle Removal	Mean % Particle Removal	Previous Mean % Particle Removal
1	0	1.2E+05	5.3E+04	**57**	**48**	**45**
2	0	1.6E+05	1.0E+05	**36**		
3	0	1.3E+05	6.2E+04	**52**		
4	0.005	8.9E+04	2.9E+04	**67**	**74**	**76**
5	0.005	1.1E+05	2.8E+04	**75**		
6	0.005	9.9E+04	2.1E+04	**79**		
7	0.05	1.3E+05	9.1E+03	**93**	**83**	**86**
8	0.05	1.2E+05	3.2E+04	**73**		
9	0.05	1.4E+05	2.2E+04	**84**		

Table 7. 7 day headloss on the pilot filter without coagulant

Filter Headloss psi

Media	**AFM**	**Sand**
Day 1	**2**	**2**
Day 7	**4**	**4**

Table 8. Results of the 5 day continuous flow experiments

Run No.	Day No.	Coagulant Dose mg(Al)/l	Filter Headloss psi	Particle count Tank 1	Particle count Tank 2	% Particle Removal
A1	1	0	2	1.3E+05	5.9E+04	**53**
A2	3	0	2	1.7E+05	6.3E+04	**62**
A3	5	0	4	1.2E+05	4.1E+04	**66**
B1	1	0.005	2	1.3E+05	4.0E+04	**68**
B2	3	0.005	2	9.9E+04	2.4E+04	**76**
B3	5	0.005	5	1.8E+05	2.9E+04	**84**
C1	1	0.05	2	1.2E+05	2.6E+04	**79**
C2	3	0.05	3	1.3E+05	1.2E+04	**91**
C3	5	0.05	5	8.7E+04	4.3E+03	**95**
D1	1	0	2	1.4E+05	5.6E+04	**61**
D2	3	0	3	9.9E+04	3.2E+04	**68**
D3	5	0	4	1.4E+05	3.4E+04	**76**
E1	1	0.005	3	1.2E+05	1.7E+04	**85**
E2	3	0.005	3	1.6E+05	1.3E+04	**92**
E3	5	0.005	4	1.2E+05	1.7E+04	**86**
F1	1	0.05	4	1.1E+05	9.9E+03	**91**
F2	3	0.05	3	1.0E+05	3.0E+03	**97**
F3	5	0.05	7	1.5E+05	4.6E+03	**97**
G1	1	0	2	8.2E+04	3.0E+04	**64**
G2	3	0	3	1.4E+05	4.9E+04	**66**
G3	5	0	3	1.4E+05	3.7E+04	**74**
H1	1	0.005	2	1.9E+05	5.4E+04	**72**
H2	3	0.005	3	1.2E+05	8.1E+03	**93**
H3	5	0.005	4	1.5E+05	1.2E+04	**92**
I1	1	0.05	3	1.5E+05	1.9E+04	**87**
I2	3	0.05	3	1.3E+05	1.4E+04	**89**
I3	5	0.05	7	1.0E+05	7.2E+03	**93**

Table 9. Comparison of mean particle removals

PAC Dose mgAl/l	% Particle Removal			
	Batch Mode	**Day 1**	**Day 3**	**Day 5**
0	69	59	65	72
0.005	77	75	87	87
0.05	93	86	92	95

14. SURFACE CHARGE PROPERTIES OF PARTICLES

a) Figures 2 to 5 show the measured zeta potentials of surrogate particles and inactivated oocysts at 0.001 and 0.01 molar salinities, for a range of pH conditions.
b) An isoelectric point for the particles/oocysts can be determined by extrapolating the data to the pH when the particles/oocysts have a net electroneutrality and their overall surface charge is zero.
c) Table 6 shows the isoelectric points that were determined for the full range in ionic strength (molar salinity) that was investigated, with and without coagulant. Where coagulant was added, PAC was added at 0.05 mg/l (Al).
d) It can be concluded that under typical pool water conditions (0.001 to 0.01 molar salinity) coagulant addition significantly alters the charge of the particles/oocysts at the pH values approaching those experienced in practice.
e) At a pH of 7.5 to 8.0, without coagulant the particles/oocysts have a negative surface charge. Such particles/oocysts can be expected to be repulsed by the negative surface charge of the filtration media, explaining their poor removal.
f) At this range of pH and with coagulant added the particles/oocysts have a positive surface charge. Such particles/oocysts can be expected to be attracted by the negative surface charge of the filtration media under the experimental conditions used, and the coagulated particles/oocysts are larger, both explaining their much better removal by filtration.

Fig 6. Zeta potential of surrogate particles at 0.001 molar salinity

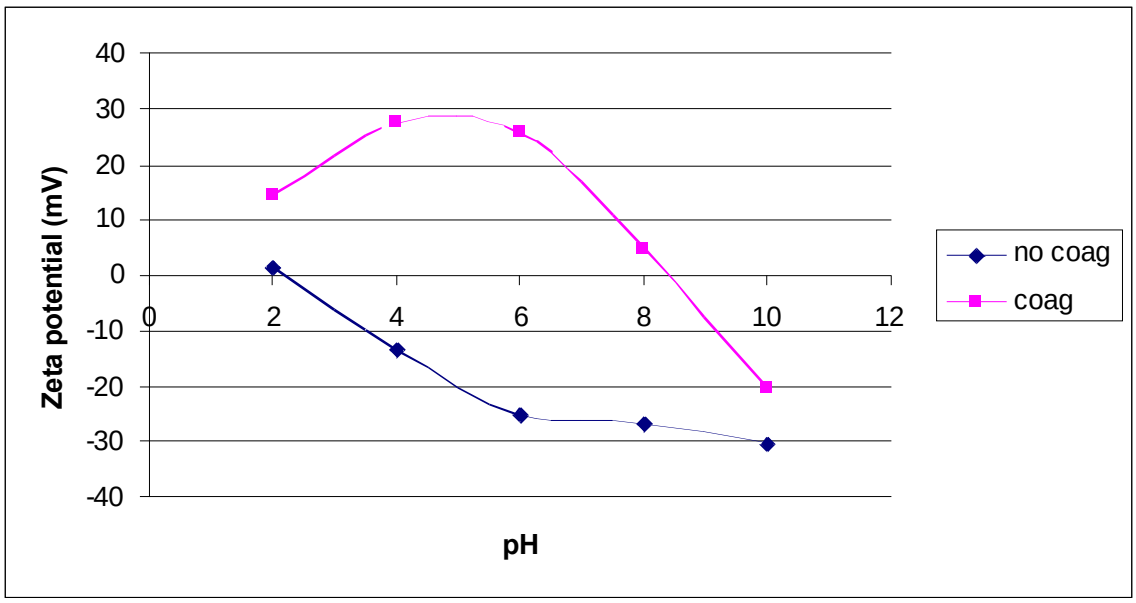


Fig 7. Zeta potential of inactivated oocysts at 0.001 molar salinity

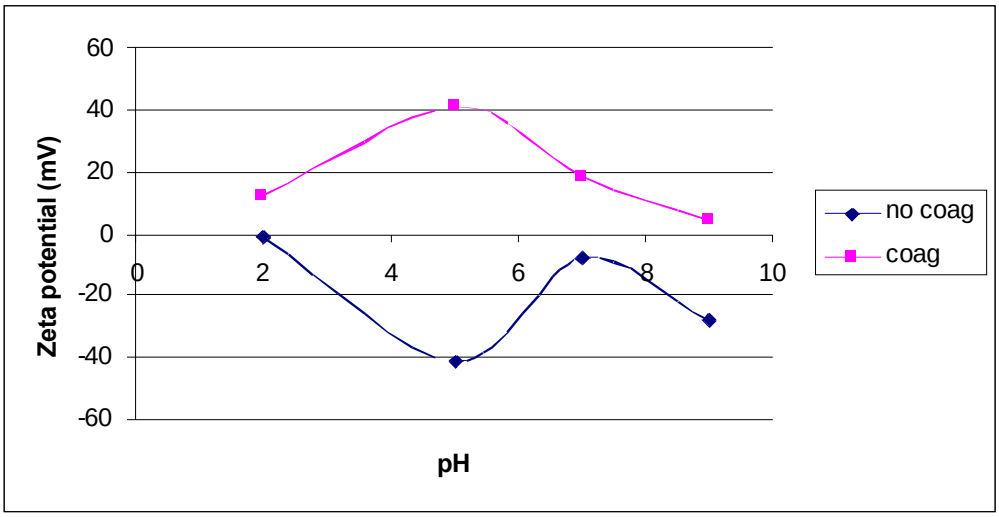


Fig 8. Zeta potential of surrogate particles at 0.01 molar salinity

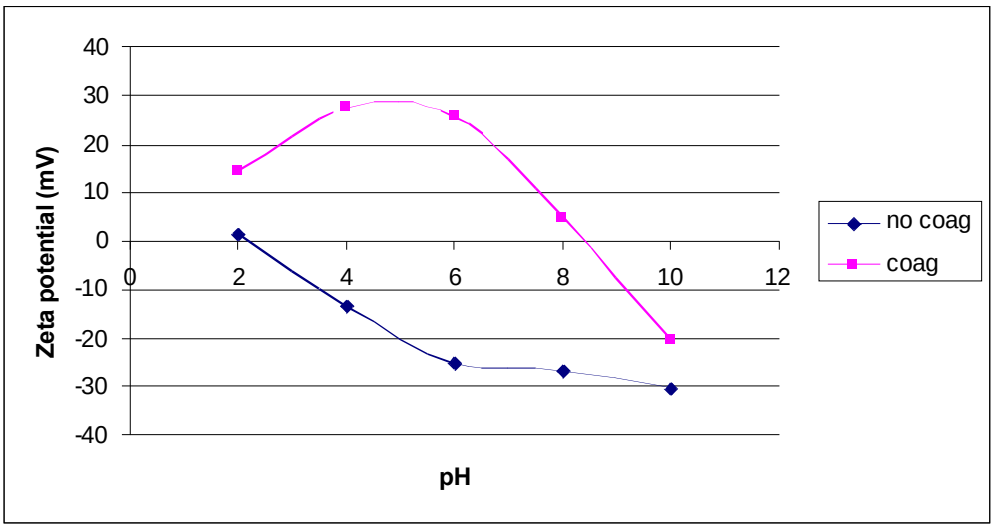


Fig 9. Zeta potential of inactivated oocysts at 0.01 molar salinity

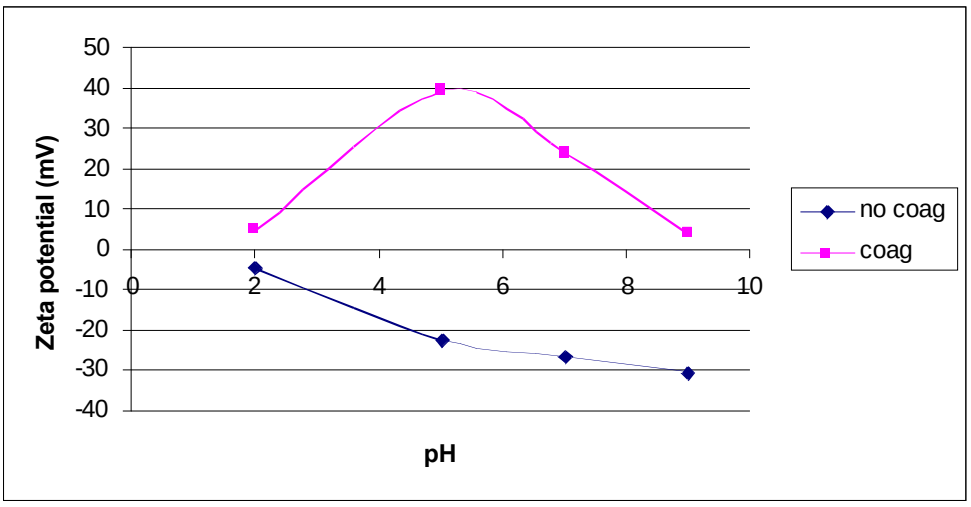


Table 10. Summary of isoelectric points determined for surrogate particles and inactivated oocysts.

	Ooocysts		Surrogates	
Ionic strength	No Coag	Coag	No Coag	Coag
0.1	3.2	9.1	3.5	7.2
0.01	1.6	9.2	3	8.5
0.001	1.9	9.5	2.2	8.5
0.0001	1.5	9.5	2.1	8.5

15. CONCLUSIONS

- Batch runs of the large pilot using oocyst surrogate particles have confirmed the results of the previous work that coagulants are required to obtain better than 90% removal in a single pass through the filter. However, removal without coagulant has tended to be a little better and removal with coagulant a little worse than in the previous experiments.
- An in-house method was developed for the enumeration of surrogate particles at the concentrations used in previous work. This greatly reduced the costs of analysis. Attempts to lower the limits of detection of the method did not provide a useful method.
- A small pilot plant has been constructed to operate in a Class 2 biological containment cabinet. This gave similar removal of surrogate particles to the large pilot plant. Removal of live Cryptosporidium oocysts improved with the addition of coagulant but removal both with and without coagulant was somewhat better than for surrogate particles.
- Basing treatment on surrogate particle removal will therefore err on the side of safety.
- Inactivated oocysts were much better removed than live oocysts without coagulant and those used were not thought to be a suitable live oocyst surrogate.
- Operation of the large pilot plant with water from the Welsh National Pool had little or no influence on surrogate particle removal either with or without coagulant.
- Two glass filter media behaved similarly to sand for the removal of surrogate particles.
- Build up of debris on sand filter media slightly improved surrogate particle removal over a 5 day period.

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Appendix 1

Agreed Research Proposal

OVERVIEW OF RESEARCH STRATEGY

The research programme that is being stimulated by PWTAG has the potential to create the leading research centre in the UK, and possibly the world, focusing on the treatment of swimming pool waters and the management of pool water quality.

The initial experimental work in 2004 is being expanded this summer, with the evaluation of the impact of a range of coagulants on high-rate filtration. This will provide quick answers to questions about the validity of using coagulants but will not address specifically the removal of *Cryptosporidium oocysts*.

To address the removal of *Cryptosporidium oocysts,* a four year programme is proposed, with funding of about £ 10,000 per annum from PWTAG being matched with slightly higher amounts from Swansea University's Master of Research (MRes) programme in the School of Engineering (funded by EPSRC). This will build very substantially on the earlier work that was undertaken in 2004. The linkage to the MRes programme confers a major cost advantage on the work insofar as the new requirement for "full economic costing" is avoided.

The first year of this MRes supported work will seek to demonstrate the equivalence of surrogate particles with live *Cryptosporidium oocysts* and the equivalence of model pool water with water drawn from an actual pool. This work will create a strong foundation for further work (in years 2, 3 and 4) using surrogate particles, in which the influence of operating variables will be investigated in detail, to enable PWTAG to determine authoritative guidance to pool operators. We will use advanced nanoscale surface characterisation techniques to determine the degree to which surrogate particles mimic the interactions of oocysts. The planned involvement of the Nanotechnology Research Centre at Swansea University will enable the further development of surrogate particles to ensure they match live *oocysts*, should this be necessary. The further work in years 2, 3 and 4 will be subject to annual review by PWTAG.

Additionally, it is planned to undertake four other projects at the Wales National Pool at either undergraduate or MRes level:

1. An audit of energy and water consumptions to identify the scope for improvement.
2. A feasibility study of the use of solar heating for localised hot water provision.
3. Three-dimensional flow analysis of water in the training and competition pools.
4. Three-dimensional flow analysis of air above the pools.

Once PWTAG has confirmed the first year of the MRes supported programme and its support in principle to the overall four-year programme, Swansea University will be in a strong position to submit a major research funding application to EPSRC (about £ 250,000) with the ambition to develop a sophisticated three-dimensional filtration model for application to the treatment of swimming pool waters. The model will be

greatly informed and influenced by the experimental programme and offers the prospect of a low cost optimisation tool being made available to pool operators.

It is likely that the momentum created by this linked research will lead to a succession of seminars and workshops as part of the overall dissemination of results, a process in which PWTAG will justly assume a position of prominence.

RESEARCH PROPOSAL to PWTAG, March 2006

SIMULATED CRYPTOSPORIDIUM REMOVAL UNDER SWIMMING POOL FILTRATION CONDITIONS

Background

Exhaustive literature reviews for PWTAG (Swansea University, 2000; B Croll, WQM 2002) confirmed that very little research had been undertaken on the removal of Cryptosporidium by swimming pool water treatment. It was concluded that the only information of any substance was that available from the treatment of drinking waters and that it's relevance could only be regarded as tentative.

During 2004, an initial three-month pilot treatment trial was undertaken for PWTAG by Swansea University, in conjunction with Water Quality Management Ltd and PWTAG members. The trial was based on a surrogate particle tracer and was undertaken using typical conditions for the treatment of swimming pool waters. The trial concluded:

- without coagulation, Cryptosporidium removal by filtration is ineffective, being less than 50%
- with coagulation, Cryptosporidium removal by filtration is effective and capable of more than 99% removal
- coagulant doses must be higher than the minimum currently recommended for the general treatment of swimming pool waters.

Justification for further research

The implications of the results from the pilot treatment trial are substantial and include:

- the installation of coagulant dosing where it is not currently practiced – apart from the installation and running costs at many thousands of pools, there would be a significant training need in relation to operatives
- the continuous use of coagulants where they are only used intermittently at present and the use of higher coagulant doses generally.

In recognition of the risks to the public from swimming in pools which are treated without coagulation, it can be foreseen that any specific recommendations to dose coagulants in relation to Cryptosporidium control (for example, by PWTAG) could readily be enforced by the Health & Safety Executive and by local authorities as part of their regulatory responsibilities. However, the extent of information gained by the pilot treatment trial was limited to only two coagulant chemicals under a very restricted range of test conditions, thereby hindering such enforcement at this time.

Whilst PWTAG can issue interim guidance to swimming pool operators, on the basis of the findings of the pilot trial, it is not in a position to provide comprehensive and well-informed guidance in relation to the wide range of circumstances that exist.

Further more detailed work will therefore be necessary.

Outline of research proposals

A programme of collaborative research is proposed involving PWTAG and Swansea University, comprising:-

- operate a smaller pilot plant, using live Cryptosporidium oocysts, for a number of test conditions to validate the results based on the surrogate tracer.
- Move the existing pilot plant to the University swimming pool and operate with surrogate particles to investigate the effects of filter run length, bather load etc. on performance
- operate the existing pilot plant, using surrogate tracer, under a broad range of conditions (flow rate, temperature, pH, chlorine concentration, filter media type and depth)
- develop a computational model of the filtration process to enable rapid site-specific investigations to be undertaken, without having to undertake practical trials, as a low-cost prerequisite to the likely future modification of numerous swimming pool treatment facilities.

Manning the Research

Swansea University, School of Engineering is developing a one year Master of Research degree (MRes) in Water Technology and Management, the first course of which will begin in Sept 2006. Each student will undertake a research project, the preliminary work for which (literature survey, familiarisation with topic and techniques) will be allowed 7 weeks from Sept to March. April to early Sept will be devoted to the research project, giving some 20 weeks of practical work. The remainder of Sept will be devoted to writing a dissertation on the project.

It is proposed that the further work on filtration would be achieved using a series of MRes student projects beginning in Sept 2006 with the first project being completed in Sept 2007.

Financing the Projects

The fees and maintenance costs for the student will be met by the University.

PWTAG would finance the costs of the surrogate particles, chemicals, consumables (for analysis), University overheads/ plant maintenance and supervision/training costs.

Year one

The University class 2 microbiological hazard facilities will accommodate a smaller but still realistically sized filtration pilot plant. This will be constructed and used to confirm the surrogate results using live Cryptosporidium oocysts.

The existing pilot plant will be moved to the University swimming pool to investigate the effects of real pool water and operation on surrogate particle removal. (see Appendix)

Year Two

Assuming that the surrogate particle removals correlate with oocyst removal, in year two the project would look mainly at the effects of filter flow rate and bed depth on surrogate removal with no coagulant, optimal coagulant and the present minimum dose recommended by PWTAG. It is estimated that some 100 pilot plant runs could be carried out per project.

Year Three

The influence of chlorine concentration and temperature will be investigated.

Year Four

The effectiveness of alternative filter media will be investigated. The pilot plant will then be operated with the filtrate recycled to the feed tank under selected conditions of operation based on the earlier results.

The University will have a project on mathematical modelling of filtration which will use the results of the work supported by PWTAG.

Costs to PWTAG

Costs for the academic year 2006/7 are estimated at £10,360

APPENDIX

YEAR ONE PROGRAMME

COMPARISON OF THE FILTRATION EFFICIENCY OF CRYPTOSPORIDIUM SURROGATE PARTICLES WITH LIVE CRYPTOSPORIDIUM OOCYSTS

Objectives of the Research Programme

1. To construct a small scale sand filtration pilot plant (20 to 50 mm id) which will fit into the Class 2 biological safety cabinet at Swansea. The pilot plant will mimic the present larger scale pilot plant which is housed in the wet lab at Swansea in terms of filter bed construction, filter downflow rates, filter bed depths and ability to dose coagulants.
2. Operate the pilot plant with Cryptosporidium surrogate particles with and without coagulants under the same conditions as were used in the previous work to ensure that the performance of the plant is close to that of the larger plant on which the previous work was performed.
3. Operate the pilot plant with live Cryptosporidium oocysts with and without coagulants under the same conditions as in 2. above and compare performance with Cryptosporidium surrogate particles.
4. Investigate the surface charges and properties of surrogate particles and live oocysts and relate this information to the pilot plant results.
5. Move the large pilot plant to the University Swimming Pool and operate in a similar manner to the main pool plant with and without coagulants, monitor. Introduce spikes of Cryptosporidium surrogate particles under different bather load conditions and monitor.

Outline Experimental programme

Literature Survey (Sept to March)

Survey the literature in order to gain the latest information on the comparative sand filter removal efficiencies of Cryptosporidium surrogate particles and Cryptosporidium oocysts.

Analytical Techniques (Sept to March)

1. Train in surrogate particle analysis with ESL Ltd who produce the particles.
2. Transfer the analysis to Swansea and produce analytical quality control information.
3. Train in analysis of live Cryptosporidium oocysts and produce analytical quality control information.

Small Pilot Plant

Familiarisation and Calibration (Sept to March)

1. Assist in the construction of the pilot plant
2. Calibrate flow gauge and dosing pump.
3. Operate pilot plant and recheck calibrations whilst operating.
4. Familiarise the pilot plant in all working modes, flowthrough, recirculation and backwashing.

Training on Sterile Techniques (Sept to March)

1. General training
2. Pilot plant specific training

Operation with surrogate particles (4.5 weeks +? weeks)

1. Operate using surrogate particles, under the same conditions as used in the previous work without coagulant and with PAC at 0.005 and 0.05 mg/l as Al. All runs to be in triplicate. (total 27 runs at 6 runs per week. 4.5 weeks)
2. It is expected that the runs with coagulant will give statistically significant results for percentage removal of particles. If not perform further replicates until a significant result is obtained.
3. It is expected that the results without coagulant will not give a statistically significant percentage particle removal. If so assess the results and decide at the time whether it is practical to perform sufficient replicates to obtain a significant result.
4. Compare the results with those of the earlier work. They should be close.

Operation with live oocysts (4.5 weeks +? weeks)

1. Operate using live oocysts, under the same conditions as used in the previous work without coagulant and with PAC at 0.005 and 0.05 mg/l as Al. All runs

to be in triplicate. (total 27 runs at 6 runs per week. 4.5 weeks). The spike of oocysts needs to be such that a 99% removal can be detected in a reasonably small sample with a simple analytical technique

2. It is expected that the runs with coagulant will give statistically significant results for percentage removal of oocysts. If not perform further replicates until a significant result is obtained.
3. It is expected that the results without coagulant will not give a statistically significant percentage oocyst removal. If so assess the results and decide at the time whether it is practical to perform sufficient replicates to obtain a significant result.
4. Compare the results with the removal of surrogate particles.
5. Propose further work if necessary.

Surface Properties of surrogate particles and oocysts (5 weeks)

1. Electrophoretic measurements. Comprehensive characterisation of surface potential of surrogate particles within different aqueous environments including ionic strength and pH variations and model swimming pool waters.
2. Size distribution studies of surrogate particles
3. Comprehensive characterisation of surface potential of oocysts within different aqueous environments including ionic strength and pH variations and model swimming pool waters to determine whether surrogate particles match this colloidal behaviour.
4. Size distribution studies of oocysts measured to determine whether this matches the size distribution of surrogate particles
5. Adhesion measurement using hydrodynamic shear assays to study the attachment of particles and oocysts to model surfaces in key aqueous environments identified in previous experiments.
6. Data analysis; electrophoretic measurements used to analyse the adhesion measurements and determine the interrelationship of the physiochemical forces controlling adhesion and whether this matches for surrogate particles and oocysts

Future research, the influence of environmental additives that change the surface chemistry and so interactions between oocysts, using the same research strategy established within baseline studies above. Atomic force microscopy determination of the surface roughness of surrogate particles and oocysts; does it match. Surface modification of surrogate particles to improve similarity to oocysts through covalent bonding of proteins to particles.

Large Pilot Plant

Move to University Pool (3 weeks)

7. Move pilot plant to the University Swimming Pool. Organise for the plant to run on pool water before coagulant addition and filtration but after pH correction. (2 weeks)
8. Familiarise with the operation of the pilot plant (2 days)

9. Calibrate flow gauge and dosing pump (2 days)

Operate without Coagulant (1.5 weeks)

1. Operate on the pool water at 25 m/hr filtration rate for the normal main pool filter period between backwashes (assume 1 week).
2. Monitor for turbidity, preferably continuously on input and filtered water. Monitor filter headloss. Preferably monitor also for particles.
3. At two periods, one at low bather load and one at high bather load add surrogate particles to the filter input and sample the filtered water and input water.
4. Compare results with earlier results using tapwater.

Operate with coagulant (3 weeks)

1. Repeat the previous paragraph but with PAC added at 0.005 mg/l as Al and at 0.05 mg/l as Al.
2. Compare the results with the earlier results using tapwater.

Operate at the higher coagulant dose for any remaining period

1. Monitor headloss build-up as well as the other parameters.

Estimated Costs

Tracer			£1550
Consumables, chemicals (analysis and pilot plant)			£635
New pilot plant			£4000
Supervision	3 days @ £500/day	£1500	
	3 nights bed/breakfast	£120	
	3 days subsistence	£15	
	3 journeys of 450 miles @ £0.4/m	£540	
			£2175
University overheads/maintenance/services			£2000
Total			£10360

APPENDIX 1.

ANTICIPATED WORK PROGRAMME

1. **Literature Survey**

   Familiarisation with the pilot plant will also be undertaken during this period of 2 weeks.

2. **Operation of present Pilot Plant**

   Using jar tests establish tracer dose and it's coagulation/flocculation behaviour.

   All runs to be performed with a 600mm (800mm) deep sand bed. Chlorine concentration to be 1 to 1.5 mg/l free chlorine, alkalinity, and calcium concentrations as in the 2004 experiments. pH 7.2 to 7.4.

   All sets of conditions to be run in duplicate.

   Operate pilot plant runs (as in previous Cryptosporidium work) with the clay surrogate at 25 m/hr filtration rate both without coagulants with PAC doses of 0.05 and 0.005 mg/l as Al, with aluminium sulphate doses of 0.05 and 0.5 mg/l as Al and with a cationic polyelectrolyte at the minimum dose recommended by the manufacturer and an agreed higher dose.

   Repeat at 50 m/hr filtration rate.

   Monitor using turbidity and Al residual where appropriate.

   This amounts to 28 filter runs, or at 8 runs per week 3.5 weeks work.

3. **Improving flocculation or decreasing flocculation time**

` If filtration at 50 m/hr above gives poor performance with coagulant, then increase flocculation time to correspond to 25 m/hr conditions.

   If filtration at 50 m/hr gave good performance in 2. above, then reduce flocculation time to be similar to an operational filter (the pilot filter presently has a longer flocculation time than most operational filters). Run with both coagulant concentrations for the coagulants in 2 above.

   Either option, modification of pilot plant plus 12 runs, 2 weeks.

4. **High rate, shallow sand bed**

   300mm sand bed 50 m/hr run without coagulant and the coagulants used in 3 above at the two concentrations. 14 runs, 2 weeks.

5. Total Time

Estimated at 10 weeks including writing up time, if the above work is completed ahead of estimated time then experiments with recirculation of the filtrate to the feed tank will be undertaken.

1. Run in recirculation mode at 50 m/hr without coagulant and at the two coagulant doses using the best coagulant found. Slug dose the feed tank with surrogate and measure the falling feed tank concentrations.
2. Run with a semi continuous feed of surrogate designed to mimic the input of turbidity into a pool with and without coagulant. Each run to be for at least 24hr, 12 hrs feeding surrogate and 12 hrs without to represent overnight filtration.

6. Estimated Costs

Student	10 weeks @ £200/week	£2000
University overheads/supervision/maintenance		£3000
Supervision	4 days @ £500/day	£2000
	Travelling/subsistence	£900
Materials/chemicals		£500
Turbidimeter		£1000
Aluminium analysis		£500
Total		£9900

Appendix 2.

Pilot Plant Operations

TO HEAT AND MIX WATER IN TANK No1 (Separate circuit from the filter)

1. Switch on pool heater
2. Set pool heater control to the desired temperature (normally $30^{O}C$)
3. Close valves V20, V24
4. Open valve V22
5. Switch on pump P1
6. Adjust V21 to give the desired recirculation rate

TO RECIRCULATE WATER THROUGH THE FILTER BACK TO TANK No1

1. Open valves V4, V5, V8,V11, V13, V15
2. Close valves V6, V10, V14, V16, V17
3. Leave valves V20, V22, as set with V24 closed
4. Switch on pump P2
5. Partially open valve V6
6. CloseV15
7. Adjust flow to the desired value as measured by the rotammeter flowmeter by adjusting valves V5 and V6. Closing V5 will increase the flow, opening V6 will increase the flow.

TO SEND FILTERED WATER TO TANK No2

1. Open valves V4, V5, V8, V11, V13, V15.
2. Close valves V6, V10, V14,, V16, V17
3. Leave valves V20, V22, as set with V24 closed
4. Switch on pump P2
5. Partially open valve V6
6. Close V15
7. Adjust flow to the desired value as measured by the rotammeter flowmeter (normally 450 l/hr) by adjusting valves V5 and V6. Closing V5 will increase the flow, opening V6 will increase the flow.
8. Close V13, Open V14

TO CHANGE FROM RECIRCULATION TO TANK No1 TO FLOW TO TANK No2

1. Close valve V17
2. Open valve V14

3. Close Valve V13

TO CHANGE FROM FLOW TO TANK No2 TO RECIRCULATION TO TANK No1

1. Open Valve V13
2. Close Valve V14

TO BACKWASH FILTER

1. Ensure there is sufficient water in tank T1 (at least quarter full)
2. Leave valves V20, V22, as set with V24 closed
3. Open V4, V5, V15, V10
4. Partially open V11
5. Close V6, V8, V13, V14, V16, V17
6. Switch on Pump P2
7. Adjust the flow using valves V5 and V11
8. The flow should be such as to produce about 25% sand bed expansion
9. Backwash until the water from the top of the filter runs clear but at least 5 min

TO CHANGE FROM FILTRATION TO BACKWASH

1. Open V15, V10
2. Close V8, V6, V13, V14
3. Partially close V11
4. Adjust flow as above using V5, V11

TO CHANGE FROM BACKWASH TO FILTRATION

1. Open V13
2. Close V10
3. OpenV8, V6, V11
4. Close V15
5. Adjust Flow using V5 and V6

TO SHUT DOWN

1. Open V15
2. Switch off Pump P2
3. Close V13, V14
4. Close V15

Appendix 3

Outline of the In-house Analytical Methodology for Surrogate Particles

1. 100ml samples of T1 (the feed tank to the pilot filter) and T2 (the filtered water) were taken every 10 mins during 60 min runs (25m/hr) or every 5 mins during 30 min runs (50m/hr). These samples were combined to give a 600ml composite sample of each of T1 and T2.
2. The T2 samples were filtered under pressure, see Fig A3.1 and Diagram A3.1, to a measured volume of approx. 10 ml, using a membrane filter of pore size 0.0025μm and 50mm diam. Later the membrane pore size was changed to 0.2 μm in order to speed filtration.
3. The concentrated sample and the membrane were transferred to a 100ml wide-neck sample container and vibrated using an ultrasonic bath for 10 min. This served to dislodge the particles from the membrane and provide an homogenious suspension of surrogate particles.
4. 25 μl samples of either the original 600ml sample (T1) or the concentrated filtrate were placed in an haematometer cell of known volume and the number of particles in the cell counted by eye using a backlit microscope with both normal and fluorescent illumination.
5. From these measurements the number of particles in the original 600ml samples can be calculated.

Fig A3.1 Pressure filtration apparatus

Fig A3.2 Sample Container and Filter base

Fig A3.3 Pressure Membrane Filtration Cell

Fig A3.4 Haematometer Cell

Fig A3.5 Inverted Microscope