THE EFFECTS OF FLOW RATE CHANGES ON FILTER PERFORMANCE

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ABSTRACT

Filtration is an essential process within potable water treatment. Recent outbreaks of Cryptosporidiosis have brought filter performance into the spotlight, as it is widely acknowledged to be the most important stage for the removal of pathogens. There are many variables which can affect the efficiency of filtration, both within the filter itself, such as media type and size, and also stages preceding filtration such as coagulant dosing.

This research focuses on the effects of flow changes on filter performance, because although researchers as early as the 1960's have suggested that increasing the flow will increase particulate breakthrough, no attempts have been made to actually quantify or explain these effects.

Work has been carried out at laboratory and full-scale, and computer simulations have also been conducted. In the laboratory, temporary, permanent and gradual flow increases have been applied to a 1m bed in a 2m high filter column. These increases were of varying magnitude and at different stages of the filter cycle, to determine which type of flow change is most harmful in terms of increased particle breakthrough. Various media configurations and coagulants have been investigated. The effluent quality was recorded using a particle counter, rather than a turbidimeter, so that the particle size distribution of the breakthrough could be assessed. Breakthrough in the specific Cryptosporidium size range (2-5µm) could be distinguished.
The results have shown that in general, flow increases do cause an increase in particle breakthrough, and that the larger and later the flow change is applied, the higher the level of breakthrough is observed. However, this pattern was not observed in all cases, and it was clear that external factors are just as important as the flow change itself in determining the amount of breakthrough from the filter. One of the most important variables is water temperature. Results have shown that when using alum as the coagulant, an identical flow change will cause more breakthrough at higher water temperatures than that observed during periods of colder influent water. Poly-aluminium chloride provided more consistent breakthrough patterns through a range of water temperatures, but this coagulant did not perform as well as alum in cold influent conditions.

The effects of mechanical vibrations on breakthrough was also investigated, and although there has been very little published research on this phenomena, this work found that vibrations have a great effect on the filter performance, both at laboratory and at full-scale.

All of these results suggest a very complex pattern of filter breakthrough, whereby a number of factors must be considered when trying to predict the amount of particle shedding during a particular flow change.
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1 INTRODUCTION

Drinking water treatment is a complex process and relies on the correct operation of each stage of the process in order to provide high quality potable water.

The basic processes involved in water treatment are; screening to remove large objects such as leaves, chemical dosing to destabilise the suspended particles in the water, sedimentation to remove the majority of particles, filtration to remove the remaining particles and finally disinfection to kill any remaining pathogens. These processes vary from plant to plant, and additional stages such as dissolved air flotation (DAF) and secondary filtration maybe used where required. All of these stages collectively strive to provide water that meets ever increasingly stringent standards.

Water quality issues have been raised in the public domain with several highly publicised outbreaks of waterborne diseases, Cryptosporidiosis in particular. These outbreaks, such as those in Swindon in 1988 and Milwaukee 1993, caused a large overhaul in water standards, and the publication of 2 Badenoch reports which suggested new working practices for water treatment plants. However, the latest Cryptosporidiosis outbreak in Glasgow in August 2002, suggests that there is still more to be done to ensure that the water consumed is of the highest quality possible.

One of the most important processes is the filtration stage, especially when considering the fact that Cryptosporidium is resistant to most forms of disinfection. Filtration involves passing pre-treated water through a bed of granular material which removes the suspended particles as the water flows by. This immediately gives the impression of the granular media sieving the sediment out of the water. However, in reality the particles in the water are several magnitudes smaller than the media grains,
so it is actually a more complex process of interactions between the particles and the grains, whereby van der Waals and electrostatic forces attract the particles.

The media is contained within structures so that the water flows down under gravitational forces through approximately 1m of media. This depth is usually sufficient to provide satisfactory filtration. There are several types of granular media that can be used, for example sand, anthracite and granular activated carbon (GAC). The type chosen is usually specific to the needs of the individual plant.

There are many factors that can affect the performance of the filtration process, and great care must be taken when designing the filtration system to ensure optimal operation. These factors include the amount of solids going onto the filter (i.e. the solid loading), the flow rate of the influent suspension, and whether this rate is subject to fluctuations, the type and dose of coagulant used and finally the influent water temperature. Some of these factors will be investigated in more detail in this project.

Filters cannot continue to provide high quality water indefinitely, and after a certain time either the headloss reaches unacceptably high levels (due to the particles clogging the media pores), or particle breakthrough levels rise as flocs are detached from within the filter and removed into the effluent. When either of these occurs, the filter must be cleaned. There are several methods of backwashing the filter, (as described in more detail in chapter 2.3) but all generally involve passing water and/or air back up through the filter to remove the particles that have coated the media grains. The efficiency of this process greatly influences the subsequent performance of the filter, because if the media is not cleaned properly, the remaining solids left in the bed are likely to be transported into the effluent once the filter is started up again.
Once the correct design and cleaning processes have been established, the filter should be able to cope well with a range of influent conditions, and provide high quality water during normal operation. What remains less clear is how well the filtration process copes during periods of unstable operation, i.e. flow changes and external effects such as vibrations. This research is intended to provide this information, and will investigate at a range of levels, from computer simulations to full-scale studies.

1.1: **Aims of the research project**

There have been many studies over the past 4 decades to investigate various aspects of the filtration system, and the overall process of particle capture is fairly well known. However one area where there has not been extensive investigation is what happens to the particles within the filter during a flow change, and which flow changes cause most breakthrough.

The main aim of this project was to investigate the effects of flow changes on the filter performance as a whole, and the objective was to introduce several different types of flow change on a laboratory filter column and record the subsequent particle breakthrough.

Special attention was paid to the 2-5\(\mu\)m size range as this represents the Cryptosporidium size range, and the reduction of potential outbreaks of Cryptosporidiosis was the driving force behind this research. However, as pathogens may be contained within larger flocs, the size ranges >5\(\mu\)m were also recorded. No
oocysts were actually used in this study, due to the inability to inactivate and fluoresce the cysts themselves in the laboratory. In this respect, only the potential risk of a *Cryptosporidium* outbreak could be assessed, based on the fact that at full-scale plants, particle breakthrough in this size range could be oocysts.

As well as performing filter runs on the laboratory column, additional processes were investigated, such as coagulation at a range of temperatures, and floc development both before and within the filter. The results of which would assist in providing a comprehensive view of particle breakthrough under a range of process variables. Another aim of the research was to see how the laboratory results could be compared to full-scale operation. This involved spending time at several water treatment works and recording the breakthrough patterns of the filters. In addition, for every laboratory run performed, a corresponding run was carried out on a computer simulation model, Filterflex. The results evaluated whether the model could successfully be used as a predictive tool for filter breakthrough.

Initially, the desired outcome of the project was to provide some operational parameters that could be used at treatment plants to introduce flow changes (created by backwashing and increases in demand) in such a way as to limit the amount of additional breakthrough.

As the project progressed, it became clear that this would not be possible as there were too many variables that could affect the shedding. The research changed tack slightly to provide a thorough investigation of the processes before, during and within the filtration cycle that cause breakthrough, and how flocs behave during flow changes.
2 LITERATURE REVIEW

The filtration process is arguably the most important part of water treatment. There are a number of variables which can affect the efficiency of the filter. Within the filter itself, the media type and size used, the backwashing regime, and the influent flow rate are all important. Similarly, the processes preceding the filter, such as coagulant choice and dosing rate must be optimised to aid the filter operation. All of these processes must work in conjunction with each other to provide high quality water. This chapter explains these processes in more detail, along with the methods used to monitor the effluent water.

2.1: Types of filters and filtration processes

Filtration of suspensions through porous media is an important stage in the treatment of potable water to achieve final clarification (Tebbutt, 1992). There are two main types of filter, Slow Sand Filters (SSF) and Rapid Gravity Filters (RGF). SSFs however are less frequently used in modern potable water companies, as they are slow and take up a large area (having said this, they are still used successfully by Thames Water in the UK). They may be suited to developing countries as they use low technology. In drinking water treatment plants, rapid gravity filters are designed to function as depth filtration units (Amirtharajah, 1988). Filtration is a widely researched and documented operation, from early pioneers in the field such as Cleasby and Ives in the 1960’s, who worked on the basic concepts of filtration, to today’s researchers such as Carlson and Johnson (2001), who use the latest technology such as laser turbidimeters to analyse the microfiltration processes.
Amirtharajah (1988) wrote a comprehensive review concerning filtration mechanisms. He reported that filter performance is influenced by many factors such as the physical and chemical characteristics of the filter media, the suspension flowing through it, as well as the operational practices of the filter itself. In general, the particles in suspension are much smaller than the media pores, in most cases the pores are 100–1000 times larger than the particles themselves, and so it is obvious that it is not just a case of the particles being unable to pass through the pores. Instead, other forces must be acting upon the particles for them to be held in the filter.

Amirtharajah stated that the particles attach to the filter media either by electrostatic interactions, Van der Waals forces or chemical interactions. Once the particles slow down on approaching a media grain, they are captured by these forces and then they too act as collectors. Ives (1982) illustrated that for particles to be collected, they must first cross through the streamlines around the media grains and that for water filtration, diffusion and sedimentation are the most important transport mechanisms. This is illustrated by (2) and (3) in Fig. 2.1.

Fig. 2.1 Transport mechanisms of filtration (Ives, 1982).
Diffusion is more likely to affect those particles <1μm as it results from Brownian motion of the water molecules, pushing the particle close enough to the collector. Sedimentation however is a function of gravity and the settling velocity of the particle, causing it to cut through the streamlines. This process requires particles of a larger and denser nature and so sizes >1μm are more likely to be trapped by this method.

Filtration is by no means a static process. There are several stages that a filter goes through within a single run, and many factors can affect the duration and overall outcome within these stages, such as water flow rates and influent water quality. Filter ripening is a well known process. Clark et al. (1992) stated that ripening is the increase in removal efficiency that occurs for some time after each backwash (This is the process of cleaning the filter and is discussed in more detail in section 2.3). This occurs because particles becoming attached to the filter media aid in the subsequent collection of other particles, thus improving the overall effluent quality. It is well documented that effluent quality is much higher after approximately the first hour of the filter run and that this quality is then maintained for some time before deteriorating (Amirtharajah and Wetstein, 1980).

Clark et al. (1992) examined this efficiency in more detail by designing experiments to analyse the effects of particle and media size on removal. They found that the effluent particle size distribution varied over the duration of the filter run, a result which is masked by only taking turbidity measurements. Particle sizes between 6μm and 13μm were least likely to be removed by the filter. The identification of removal efficiencies for particular particle sizes is desirable for risk analysis of potential
pathogenic organism outbreaks, as they usually have a distinct size range, although the pathogens can also be contained within larger flocs. It was also found that large media sizes resulted in low effluent quality, although removal occurred at greater depths. This result suggested that multiple layers of different media sizes are preferable (Moran et al. 1993).

It is the early stages of filtration that are of great concern as studies suggest that >90% of particles that pass through a filter do so during the initial stages (Amirtharajah 1988). However, ripening and subsequent high quality filtration does not continue indefinitely. Moran et al. (1993) and many others have conducted experiments to show that after a certain length of time, the effluent quality starts to deteriorate and this can be attributed to breakthrough.

Breakthrough is a function of two factors, reduction in particle attachment efficiency and particle detachment. The latter factor has been qualitatively analysed by Ives (1989) and others and in all cases, the media grains were observed to firstly accumulate sediment largely on the top of the grains. As more particles were deposited, the accumulations became unstable and were detached. This process continued throughout the depth of the filter, eventually leading to breakthrough into the effluent. Clark et al. (1992) stated that detachment occurs in the later stages of filtration as a build up of particles within the media causes interstitial velocities to increase so that shear forces overcome the attachment forces. Previous studies were unable to differentiate between detached particles and those passing straight through the filter from the influent water. Moran et al. (1993) however, carried out an experiment in which the influent water was switched to reduced particle water during the last few hours of a filter run to establish how much of the breakthrough was
attributed to detachment. (An implication of this could be that any *Cryptosporidium* initially removed by the filter could be re-entrained into the effluent.) The result was that the concentrations of all particle sizes >1.4µm increased after the reduced suspension was passed through the filter and they concluded that detachment of previously retained particles and flocs is probably the dominant factor of filter breakthrough. Filter stability is a dynamic process that requires additional particles to maintain the balance and so was reduced when clean water was passed through the filter. The actual processes that lead to detachment, such as fluid drag forces, are dealt with in more detail in section 2.5.

Most importantly for this study, they noted that the preferential size for particle detachment is 3 -7µm, which includes the size of *Cryptosporidium* oocysts. Despite this, detachment appeared to decrease with bed depth so deep media beds may prevent actual breakthrough as detached particles are re-captured before passing out of the filter bed (Moran *et al.*, 1993). However, beds that are too deep will become uneconomical in terms of both construction and media costs, and also backwash water volumes.

The size distribution of particles during filtration has been studied in greater detail by Mackie and Bai (1993). They conducted experiments using suspensions of varying particle size distributions. They concluded that the size distribution of the influent suspension is very important for the efficiency of the filter. They found that the presence of larger particles aids in the removal of the smaller ones, as they speed up initial filter ripening (and thus efficiency). They also concluded that finer particles cause more rapid headloss development. Although this tends to even out when taken over the entire bed, it must be taken into account when developing headloss models,
as using headloss curves from the top layer of the filter alone will prove inaccurate when applied to the whole bed.

A mathematical model has been developed by Stevenson (1997a), which is based on the Kozeny-Carman equation and aims to predict particle behaviour and detachment during filtration. Both voidage and particle size distribution are included to provide a more realistic model, and shear stress values determine whether deposition occurs or not. The results produce similar features to real filters, such as the development of "wormholes". This model has been incorporated into a PC software program in BASIC, MFLX (Multilayer flexible model, now called Filterflex), which will be used to compare theoretical results with the findings of this study. This is discussed in more detail in section 2.12 and Chapter 3.8.

2.2: Media Properties

Before filtration can take place, the correct media type must be chosen for the specific task in hand. There are several factors which dictate the choice of media, for example cost and backwashing procedures. There are four main types of media commonly used:

- Sand
- Anthracite
- Gravel (Although only as a support medium)
- GAC

Sand is the most common granular media used as it is readily available, and so comparatively cheap, although only a small percentage of naturally occurring sand is
found in the optimum size range, which has been quoted as 0.5 – 1mm for rapid
gavity filters (Stevenson, 1994). Another benefit of sand is that it is very
hardwearing and so withstands attrition during backwashing, resulting in no reduction
in grain size (Humby and Fitzpatrick, 1996). It has been reported in some literature
that sand grains are rounded and that filter performance is enhanced by this fact.
However, in reality, some angularity in the grains is inevitable and this may actually
benefit filtration rates due to the altered voidage within the filter (Stevenson, 1997b).
It will also increase the surface area available for attachment.

Anthracite grains are produced by crushing massive amounts of the material until a
suitable size is achieved. This is not an exact procedure and so a wide range of grain
sizes will be produced, not all of which will be suitable for use in filtration. This
makes it slightly more expensive than sand, but is often used in conjunction with sand
for dual media beds.
Gravel is used, although mainly to support the sand or other media and prevent it
being washed out. Several grain size grades can be used, although traditional bed
design with separate air scour backwash will often only use one size of gravel to
prevent sand entering the air nozzles.
Finally, Granular Activated Carbon (GAC) can be used as an alternative to sand,
although it is predominantly used as an absorbent. It is more friable than sand and
anthracite, but it is a lightweight material that copes well with normal filtration
conditions. However it performs less well under backwashing conditions as it has a
tendency to break up and be carried away with the wash water as it has such a low
density.
Also used as media are:

Garnet – This is used in triple media filters in conjunction with sand and anthracite. (This was favoured by Anglian Water in the early 1990’s and these filters are still in operation today).

Shale and Lytag – Used in Biologically Aerated Filters, BAF’s.

Bone Char – This is used for adsorption rather than solids removal and is a type of GAC.

All of these materials, (with the exception of GAC), are fairly cheap when compared to synthetic media as they are mostly naturally occurring. However, a filter currently being developed, which uses a synthetic porous media and boasts impressive results in terms of filtration rates and economical backwashing, may offset the higher costs of the media. The media itself is unusual in that it is porous and so the suspension flows both around and through the media grains. The media is compressible and so the bed properties can be modified to suit the suspension to be filtered. Results have shown similar turbidity removal levels to conventional filters but at 6 times the flow rate, and backwashing which requires 2% water compared to 6-15% for granular media (Caliskaner et al., 1999). This improved particle removal has been confirmed by Gimbel et al. (2000), who conducted similar studies with Permeable Synthetic Collectors (PSCs), which are constructed from open porous plastic foam or non-woven fabrics of millimetre dimensions. Although he was looking at waste water treatment, the theory and potential benefits of the media remain the same.
The size of the media grains used depends mostly on the suspension to be filtered. Large grains will provide a lower headloss due to the larger pores, but only smaller grains are suitable for removal of smaller particles. Clark et al. (1992) found that media grains larger than 3.7mm diameter filtered no particles at all. Clearly, careful planning is required to provide a suitable media size.

Voidage (which can also be referred to as porosity), is the space between the grains expressed as a fraction of the total bed volume (Stevenson, 1997). It is these spaces where particles are trapped and the voidage partly determines the headloss caused by the suspension flowing through the grains. Each type of media has a different voidage; sand has a range of 36-43%, whereas anthracite ranges from 41-50% as it is more angular and so does not fit as tightly together. The voidage also varies depending on the state of the filter, i.e. whether the media has just been put in, or been backwashed, or has been subjected to air scour.

It can be seen that each type and size of media can be used for a specific purpose. However, it is common practice to incorporate more than one size and/or type of grain into the filter to provide a wider range of function and so improve the overall performance of the filter. These are called multi-media filters and usually comprise of two types of media although sometimes three are used. The grains are put into the filter in layers without any barrier between them, and ideally the grading becomes finer in the direction of flow. This is achieved by using larger grained material that is of a lower density than the fine-grained media so that it rests on top of it. The lower density of the larger grained material also means that during the backwash process, the media will be re-stratified into the correct layers, as
the less dense media will be carried to the top of the media bed. A common example of this is anthracite on top of sand. This grading has the benefit that the anthracite has larger voids (due to the larger grains), and so has a large particle holding capacity, and allows longer filter runs to be maintained, whilst the sand provides the finer filtration and so produces high quality effluent without excessive headloss. This also prevents undesirable surface filtration.

However, dual media filters have to utilise the same space within the filter as one media type would occupy and so in effect, both media beds are halved in depth. This could have consequences for the effluent quality (Stevenson, 1997). A recent full-scale experiment was carried out in Philadelphia, USA, whereby the media in four dual media filters was replaced with identical sand and gravel, but with anthracite of differing uniformity coefficients, (UC). The results showed that the lower the UC, the longer the filter runs, by as much as 50%, and the fewer backwashes required throughout the year's trial. The filter efficiency in terms of removal was also superior, with up to 38% better removal in the 2-5μm range (Yohe et al. 2002). This is likely to be due to less stratification of the anthracite with a lower UC.

Backwashing of dual media filters needs more careful design as the anthracite tends to be lost and it is more expensive to replace than sand. The cost of replacing the media is an important consideration, as a recent study by Rhaly et al.(2000) found that the filter efficiency of dual media beds at a water treatment plant decreased by 10% in 4 years. The filters were all identical in design and usage, and the reduction in efficiency was due to the ageing of the media itself, just becoming less effective in
retaining the sediment. This maybe an anomalous set of results, as four years is a unusually short time span for hard wearing materials such as sand to degrade.

There have been several experiments to test the benefits of triple media beds and even those testing five layers (Fox and Metcalf, 1974). However, the general consensus is that adding more layers does not automatically improve filtrate quality and that a well designed and operated dual media filter will provide results similar to single bed filters with longer run times (Cleasby, 1990). This is a somewhat simplistic view, as there are so many factors and variables to consider at each plant, and even within the plants themselves.

It is clear that filter media must be chosen carefully to ensure high quality filtration at reasonable cost, and to construct the beds sensibly so as to avoid high backwashing losses. This however can be reduced by the good design of wash out weirs and the correct selection of the wash regime and backwash rates.
2.3: Backwashing

Backwashing is the process of cleaning the filter bed after each filtration run to remove the particles from the bed itself. Fitzpatrick (1998), stated that this is done every 24 – 48 hours on average (although during this study, filter runs of up to 120h were observed at the full scale plants) and involves reversing the flow of water upwards through the bed. Filters used in direct filtration application, i.e. without an upstream clarification process such as flotation or sedimentation, however, can have a much shorter run time of between 6-12 hours, depending on the load (Ostrowski, J. Pers. Comm. 2000).

The effectiveness of the backwashing is important as it dictates to a large extent the immediate effluent quality of the next run (Cleasby et al., 1975, Amirtharajah, 1993). Cleasby and Logsdon, (1999), have also stated that the backwashing system is the most frequent cause of filter failure. Suggestions have been made by Kawamura (1991) that backwashing sequences at plants are too long and are detrimental to the filter by prolonging the ripening period of the following run. Caution must be taken with this view, as any sediment left in the filter is likely to cause a turbidity spike in the short term, and in the longer term cause “mudballing” within the filter.

In the past there have been three main methods of backwashing, firstly with water alone, secondly using air scour and thirdly a combination of the two (Tebbutt, 1992). Water washing is very ineffective in cleaning the bed and over the last two decades, water washing combined with air scour has shown to be the more effective. There are two main regimes for this, for example separate air scour backwash —“SASBW”, and combined air scour backwash, “CASBW”, i.e. air scour followed by air and water
together, finished off with a water only rinse. Amirtharajah (1993) reported on the progress and performance of combination backwashing, in which he outlined the mechanisms of the process and also optimum parameters for effective cleaning.

Another important consideration for successful filter cleaning is the design of the washwater system. This is plant specific and there are many variables to consider. Washout troughs are located either to one side or in the middle of the filter bed. These may contain baffles to help retain the media, and/or siphons to speed drain down times. There may be surface jets positioned to aid the movement of the sediment into the washout troughs. The height of the trough determines how much bed expansion can occur during backwashing, and this varies widely between plants. Some plants leave only 0.15m between the expanded media and the trough, whereas others have a gap of over 1.5 metres (Logsdon et al. 2000). All of these factors must be considered when designing a backwash system, and as always, a balance must be made between cost and filter efficiency.

Fluidisation occurs when the backwash water balances the weight of the media grains (Fitzpatrick, 1998) and so flow rate is occasionally expressed as a percentage of the minimum fluidisation velocity ($V_{mf}$). This enables patterns and characteristics to be expressed quantitatively. Amirtharajah (1993) reported on different phases of air motion by considering the airflow rate to be fixed and to vary the water flow rate from 0 to 100%$V_{mf}$. He found that at low velocities ($<10%V_{mf}$) the air bubbles moved through the media with little disturbance to the grains. At 10 – 20% $V_{mf}$ air cavities form and expand, and at 25 – 50% $V_{mf}$, air cavities formed on top of each other, causing the lower cavity to collapse and giving rise to the term “collapse – pulsing”.

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This activity caused the greatest amount of abrasion among the media grains and thus the greatest detachment of particles. At higher velocities, as the bed approaches fluidisation, this phenomenon reduces and at 100% $V_{mf}$ air is able to move freely through the bed.

Fig. 2.2 shows the passage of air through the filter at varying velocities, including those which induce collapse pulsing, and Fig. 2.3 illustrates the grain motion during this air scour.

Fig. 2.2 Schematic of air motion corresponding to conditions below, at and exceeding collapse – pulsing (Amirtharajah, 1993).
Fitzpatrick (1993) has taken these observations further with the use of video endoscopy (which is reviewed in more detail in section 2.9). Her experiments involved viewing and analysing a number of backwashing variations, using water and
water with air combinations for both clean and clogged beds. For experiments using water alone, it was found that up to \(50\% V_{mf}\), no grain movement was observed but after that, it was random and jerky. Clogging the bed with kaolin reduced the required velocity to produce movement due to smaller pore spaces. Once the bed was fully fluidised, all loosened deposits were flushed out and grains were observed to have random velocities and direction due to uneven washwater distribution.

Air scour alone was observed to only activate the top few centimetres of the filter bed, although some parts of the bed were left unmoved as the air rose through distinct passages (Fitzpatrick, 1993, Amirtharajah, 1984, 1993). This resulted in ineffective filter cleaning. Collapse-pulsing was observed to be the most efficient backwashing mechanism with grains moving in a highly agitated state and good bed circulation ensuring that all deposits were detached and removed. This reinforced Amirtharajah’s earlier observations. It also provided the most economical procedure as it requires the least wash water and after 1 – 2 minutes of collapse – pulsing, all grains were observed to be free of deposits. Fitzpatrick recommended that backwashing with air and water should be followed by a short fluidising wash to flush out all the trapped air and remaining deposits. This fluidising value will vary, dependent on the temperature of the water. Warm water has a lower viscosity, and so will require a higher water rate to provide the same amount of expansion. The temperature should be monitored so that there is sufficient flow for fluidisation, but that it is not so great as to wash media out into the troughs. This also has implications for the amount of washwater used. In warmer periods, if the backwash times remain the same, more water will have been used in the cleaning process. Plants need to ensure that the washwater tanks
have sufficient capacity for this extra water, as failure to do so will limit the productivity of the plant (Logsdon et al. 2000).

The use of video also enabled the forces acting on the grains to be observed. Fluid shear forces were found to be dominant during backwashing (Ives and Clough, 1985, Fitzpatrick, 1993). This force cannot increase beyond fluidisation however so other means of increasing the force are required. Fitzpatrick found that when air/water backwashing is at the collapse – pulsing stage, the bed itself contracts, thus reducing porosity and so increasing the fluid shear forces.

Another parameter on the effectiveness of backwashing is the characteristics of the filter media. Fitzpatrick (1998) reported on the bed behaviour of different filter media during backwashing. The media investigated was Granular Activated Carbon (GAC), anthracite, garnet and sand, alone and in multi layers. One observation was that collapse – pulsing caused destratification which is only rectified upon full fluidisation. Also, collapse – pulsing causes attrition among the grains, which reduces grain size and careful filter design is required to prevent finer filter material being lost over the backwash overflow. GAC was observed to suffer the highest percent loss due to attrition. Obviously, careful consideration is needed both in the media type used, and also the filter design itself to ensure optimum, backwashing conditions with minimal media losses.

Dual media experiments have also been conducted at plant in Atlanta, Georgia, to confirm the collapse – pulsing equation, formulated by Amirtharajah et al. (1991):
\[ aQ_a^2 + \% (V_{mf}) = b \]

where \( Q_a \) is the air flow rate
\( \% (V_{mf}) \) is the water flow rate
\( a \) and \( b \) are constants.

The experiments confirmed that this general model is successful in predicting collapse – pulsing conditions and concludes that it is the most effective filter cleaning mechanism.

Hall and Fitzpatrick (1998) have also developed a mathematical backwash model, focusing on the operational requirements (i.e. the volume of deposit to be removed) based on a fluidising water wash. Two phases of the backwash process were noted, the transient phase whereby the bed expands as it becomes fluidised. Deposits are moved into suspension as the grains are moved apart. The steady state occurs after full fluidisation and where deposits are detached by water shear, which is then flushed from the layer. Volumes of deposit within the media layers were algebraically calculated, and a backwash model was formulated from which it is possible to determine the volume of deposit remaining within the filter at any one time. The obvious downfall to this model is that it is for water wash only and does not make any allowance for air scour. It could however be applied during the final fluidisation period of an air/water backwash. Alternatively, it could be modified in some way to allow for air/water conditions.

Several studies, for example Koudjonou et al. (1999), have focused on the backwashing process with regard to filtrate quality. Several experiments were conducted, analysing a combination of air scour and water wash durations, as well as slow start up procedures following the backwash. They concluded that prolonged air scour during backwashing causes increased turbidity at the filter start up, unless extra rinse water is used, which is uneconomical.
Slow start up produced higher quality filtrate although there was no significant improvement with a 20 minute slow start compared to a 10 minute start up. Overall they recommended that for high quality effluent, the best combination was a delay after backwashing followed by a slow start. However, there is no mention of the economics of such a procedure, especially when considering a plant with a high water demand. A previous study by Colton et al. (1996) conducted similar experiments and found that the media size could influence the effectiveness of the backwashing. Four minutes of collapse pulsing was found to be optimal for 16/30 sand, after which the subsequent filtrate quality actually decreased. However, when 5/8 sand was used, the longer periods of collapse pulsing improved the filtrate quality. They also confirmed that slow start up procedures improved the performance of the filter, but that as with the collapse pulsing, the optimum duration of the slow start depended on the media size.

Another common option is to adopt a “filter to waste” practice for the first 10-20 minutes of filtration. This ensures that the water has a much lower turbidity when put back into service and eliminates the chance of residual particles in the backwash remnants passing into supply. Burris et al. (1998) recommended that if the filter to waste period required is longer than 20 minutes, the backwashing process in general needs to be reviewed, as too much water is being wasted.

To reduce the amount of water wasted in treatment works, many recycle the backwash water back into the plant. This has as many complications as it does benefits, and is very site specific. Cornwall and Lee (1993) found that Giardia and Cryptosporidium cyst numbers were much higher in recycle water compared to the raw water. There are
several options for the treatment of the washwater. These include returning it to the head of the works, sending it to the sewage treatment processes, and in some cases it can be disposed of in surface waters (although this is strictly controlled and licensed) (Logsdon et al, 2000).

The UKWIR report (1998) made several recommendations on the treatment and usage of the recycled wash water, which included settling, to remove at least 90% of the solids, continuous turbidity monitoring and only allowing recycle water to constitute 10% of the total raw water.

2.4: Coagulation

A coagulation process is used in most water treatment plants. It involves adding chemicals to the water prior to filtration to destabilise suspended particles which would otherwise not settle, float or filter. Flocculation follows coagulation and is the agglomeration of the destabilised particles into larger flocs. The characteristics of these flocs depend on the nature of the particles and the coagulant used.

Coagulants are mainly added to increase the particle size. This is done in two ways, charge neutralisation and sweep flocculation. The first mechanism involves neutralising the surface charge of the particle, characterised by the zeta potential, to reduce repulsion with other particles and also with the media grains themselves. The zeta potential is usually negative and ranges from −10 to −40mV. Around the particles themselves is a region of oppositely charged ions, so as to balance the charge. The thickness of this cloud varies, in Thames water, it is approximately 4nm, whereas sea water is 0.4 nm. This cloud makes up the Electrical Double Layer and it
is this that must be reduced in order to allow particles to attract (Gregory, 1975). Metal salts (such as iron and aluminium, discussed below) give highly charged cationic hydrolysis products which are readily absorbed on the negative particles and thus cause destabilisation and the coalescence of the particles.

The second mechanism, "sweep flocculation" is widely thought to be a more effective means of achieving particle removal (Duan and Gregory, 2002). This method involves adding considerably higher amounts of metal coagulants than are required for just charge neutralisation. The increased solids concentration causes a more rapid growth of the hydroxide precipitate, into which particles in the water become incorporated and so are effectively removed from the water. As the hydroxide precipitates have a large, open structure, it increases the chance of more particles becoming captured. Overall, it has been found that flocs develop more rapidly and to a larger size when sweep flocculation is employed, and so a greater reduction in turbidity can be achieved.

There are two main types of coagulants commonly used, metal coagulants and polyelectrolytes, and these shall be discussed here.

Metal coagulants are either based on aluminium or iron and are popular due to their effectiveness, availability and low cost.

Aluminium sulphate (alum) is the most commonly used and is manufactured from the digestion of bauxite in sulphuric acid. Polyaluminium chloride (PACl) however, is a newer coagulant and is made by controlled neutralisation and hydrolysis of alum solutions. It comes in various concentrations of aluminium by weight. It has the
benefits of only requiring half the amount of alum to produce similar turbidity removal levels (Bratby, 1980). This has been confirmed in a study carried out in Mexico, whereby wastewater is chemically treated to provide agricultural irrigation water. Jar tests were carried out and particle size distributions were obtained for several concentrations of alum and PACl. Results showed optimum solids removal was achieved with 30mg/l PACl whereas 50mg/l alum was required to produce similar removal results (Mejia & Cisneros, 2000). PACl also is reported to have superior performance at lower temperatures and results in a lower production of sludge (Gregory & Rossi, 2001). Another use of PACl, which has been investigated by Ebie et al. (2002), is to pre-coat the filter media. Their experiments have reported particulate removal rates of 99.7% on average over 20h pilot scale runs. This was observed when a 20mg/L PACl coating solution was used in conjunction with 3mg/L dosing in the influent, thus increasing the zeta potential of the media (similar to studies carried out by Shaw et al. (2000). No mention was made to state whether the coating could withstand backwashing, which would increase operational costs. A balance would need to be made between these costs and the benefits of higher quality water. However, this is a technique which shows encouraging results for enhancing overall filter performance.

Ferric coagulants are used over a wide range of pH values from 4 to 11. Iron coagulants are preferable to alum in high pH areas. Ferric sulphate is also good at colour removal.
Polyelectrolytes are a variety of water soluble, macro-molecules which can enhance flocculation. They can be natural or synthetic. They are special polymers that have the ability to be ionised and are especially useful in highly turbid waters. Activated Silica was the first polyelectrolyte to be used but it has the disadvantage that if it is not prepared properly, silica gel forms which can block pumps and pipes and leads to reduced filter run time (Robinson, 1974). Synthetic polyelectrolytes are usually supplied as granular or fine dust powder or as liquid, since solid forms do not totally dissolve. Another problem with synthetic polyelectrolytes is that they can be highly toxic in large doses. For this reason there are regularly published lists of approved products and concentration limits.

Shelton and Drewry (1973) and others found that using metal coagulants in conjunction with polyelectrolytes resulted in better floc characteristics and subsequent removal. In this context, the polyelectrolytes are flocculant aids and suitably alter the flocs, in terms of size, density and shear strength.

However, experiments by Graham et al. (1992) used alum with a polymer to analyse colour removal during filtration. They found that all combinations of coagulants were less effective in removing colour than using alum alone. It has to ultimately be a decision taken at individual plant level, dependent on the influent water quality.

Once the coagulant has been added, flocculation takes place. There are two stages, *perikinetic* flocculation, and *orthokinetic* flocculation. *Perikinetic* flocculation arises from Brownian motion and continues only for a few seconds until the flocs are too large to be affected by Brownian motion. *Orthokinetic* flocculation is due to induced velocity gradients in the liquid which set up relative velocities between the particles thus providing the opportunity for contact (Bratby, 1980). The shearing movement of
the water is a result of either flow or paddle action. Tambo and Hozumi (1979), suggested that turbulent flow produces a floc collision rate far greater than that for laminar flow, and experiments conducted by Dyer & Manning (1999) suggest that although low shear aids flocculation, higher shear rates cause floc disintegration and reduced settling velocities. This suggests there is an optimum shear rate for flocculation, which depends on the many parameters for each individual situation.

Once it has been decided which coagulant is to be added, tests must be performed to establish the correct dose to achieve optimum flocculation. There are many variables which can affect this, for example the pH of the water and the suspension concentration to be filtered.

Jar tests are most commonly used and this involves adding varying quantities of the coagulant to separate beakers of approximately 1 litre capacity. The beakers are connected to multi-speed stirrers and the results are judged on a variety of criteria, depending on the specific use of the coagulant, i.e. floc volume, density, speed of floc formation, settlement or flotation rate, or filtrate quality after granular filtration. This latter criteria is of most importance in this study. The jar tests usually predict very closely the plant or pilot scale performance.

Recent experiments have analysed the effects of coagulation on Cryptosporidium removal during filtration and all have indicated that coagulation aids in the removal process. Ives (1995) suggested that, prior to coagulation, Cryptosporidium oocysts lie very close to the minimum size for effective filtration but that after flocculation, the agglomerated particles are much easier to remove.
Hall et al. (1995) conducted experiments using both ferric sulphate and alum to investigate Cryptosporidium removal and concluded that the coagulants are very important and that alum was especially efficient in removing Cryptosporidium. Ongerth and Pecoraro (1995) also found that by using sub-optimum coagulation doses, Cryptosporidium removal dropped from 3 logs to 1.5 logs, which represents strong evidence in favour of carefully monitored coagulation and flocculation.

The most recent research has been conducted by Coffey et al. (1999) and Huck et al. (2000). They analysed coagulation conditions with regard to Cryptosporidium parvum and Bacillus subtilis removal. They concluded that even when the influent turbidity is less than 0.3 NTU, filtration performance will deteriorate if coagulation is not optimised. They also found that Cryptosporidium removal is more sensitive to coagulant conditions than Bacillus and that particle counting was more effective than using turbidity measurements.

An alternative to chemical dosing, which is beginning to be used in treatment plants, is electrocoagulation. This involves the electrolysis of aluminium rather than adding alum salts. This has several advantages, such as a reduction in sludge production and no need for specialist chemical handling (Han et al. 2002). Experiments have been carried out at laboratory scale, comparing both types of coagulation, to investigate the efficiency of electrocoagulation in turbidity removal at a range of pH values. The results suggest that a lower aluminium dose was required to achieve the same amount of turbidity removal with electrocoagulation, and that it was less sensitive to changes in pH, which makes it a more robust coagulation process (Han et al. 2002). Although this research gives promising results in favour of this
type of coagulation, more research is required to establish its performance under a wider range of process conditions.

These recent research papers confirm the importance of the coagulation process and at plant scale, successful Cryptosporidium removal is unlikely to occur with direct filtration alone, and so optimised coagulation is vital, be it through electrolysis or chemically induced.

2.5: Shear Stress

Fluids, by their very nature, continually react to forces acting upon them by deforming and flowing. Forces acting tangentially to the fluid surface are called shearing forces. Shear stresses arise due to the fact that fluid will adhere to any surface it flows past. This causes a velocity gradient to be set up with each successive layer of fluid moving faster than the layer immediately beneath it.

Shear stress is an important mechanism of particle detachment in filtration, and several papers have analysed this detachment, especially with regard to backwashing. Detachment of particles from media grains requires the hydrodynamic forces, drag and lift, to overcome the adhesive forces. Drag is the force on the particle acting in the direction of flow whereas lift forces act normally to the flow and so move the particle away from the media grain or filter wall (Raveendran and Amirtharajah, 1995).

It is known that shear stress increases with flow velocity and so when backwashing a filter, it is advisable to use high flow rates as this causes unstable particles to detach (Ives and Fitzpatrick, 1989, Cleasby et al., 1975).
However, this would immediately suggest a potential problem with normal flow filtration, as an increase in flow rates may cause particles to detach in the downward direction and ultimately lead to breakthrough.

This is highlighted by the basic shear stress equation;

\[ \tau = \mu \frac{du}{dy} \]

Where \( \tau \) is shear stress
\( \mu \) is fluid viscosity
\( \frac{du}{dy} \) is the velocity gradient.

(Ives and Fitzpatrick 1989)

Although this only strictly applies to laminar flow, it shows that velocity is directly responsible for shear stress. Other equations can also be used to show velocity gradients are an important factor in the resultant shear stress, for both laminar and turbulent flow.

These have also been reported by Ives and Fitzpatrick (1989), and firstly the power/fluid volume must be calculated from the following equation;

\[ \frac{P}{V} = \rho g Q H \epsilon A L \quad (W \ m^{-3}) \]

\( \rho = \) Water density \( \text{kgm}^{-3} \)
\( G = \) Mean velocity gradient \( \text{s}^{-1} \)
\( Q = \) Volumetric flow rate \( \text{m}^3 \text{s}^{-1} \)
\( \epsilon = \) Porosity of sand
\( A = \) Plan area of filter \( \text{m}^2 \)
\( L = \) Length of filter bed \( \text{m} \)

This can then be used in the next equation to calculate the mean shear stress, providing the current porosity of the media is known.

\[ \text{Shear stress } \tau = (P/\mu/V)^{1/2} \]

\( \tau = \) Shear Stress \( \text{Nm}^2 \)
\( \mu = \) Dynamic viscosity of water \( \text{Ns}^{-1} \)
\( P = \) Power dissipated in fluid shear \( \text{W} \)
\( V = \) Volume of water in pores \( \text{m}^3 \)

Ives and Fitzpatrick (1989) also found that the type of deposit affects the amount of detachment by fluid shear, for example kaolin flocculated with aluminium hydroxide was more easily sheared than kaolin alone. Raveendran and Amirtharajah (1995) conducted similar experiments to analyse backwashing detachment and found that the
pH of the water also affected detachment, with higher detachment rates occurring in waters with a high pH. Although these findings were observed during backwashing investigations, they may have some bearing on the type of coagulant used at plant scale for normal filtration. Further research would be required to observe whether fluid shear preferentially detaches certain coagulant flocs during rapid gravity filtration.

2.6: Floc Strength

As stated in earlier chapters, particle removal is often greatly improved by increasing the size of the particles prior to sedimentation/flotation or even direct filtration (Gregory, 1999).

The sequence of floc formation follows a distinct pattern, firstly a coagulant is added which causes particles to coalesce. These flocs then grow in size due to mechanically induced fluid shear. However, the larger they grow, the more susceptible the flocs are to break up under the shear forces. An overall size distribution is thus achieved which is a balance between floc growth and breakage (Spicer et al. 1996).

There have been many studies which examine the structure of the flocs during flocculation, with the aim of optimising the process with regard to coagulant dosing. Two of the most important factors are Floc strength, i.e. the resistance of the floc to shear induced break up, and also re-attachment strength, which is the ability of the flocs to re-form after break up (Yeung & Pelton, 1996).

Francois & Van Haute (1984) established through many experiments that there is a four stage growth process during flocculation. These are primary particles-flocculi-
flocs-floc aggregates. He stated that a constant number of flocculi make up a floc, and similarly a certain number of flocs make up a floc aggregate. This number increases with a decrease in mixing intensity and vice versa. This was however, only derived using alum coagulants.

Jung et al. (1996) has found similar floc structures using iron hydroxide flocs. These experiments have found that at low shearing rates, the flocs re-structure but do not break up, but at high shearing rates, the flocs break up and do not reform.

Traditionally, these variables have been examined using jar tests, and theoretical floc-strength models have been developed based on these results. These models assume that floc break up falls into two categories. “Surface erosion”, whereby particles are removed from the surface of the floc by shear stresses, and “large-scale fragmentation” which results in the floc breaking into similar sized pieces. The latter was attributed to tensile stresses across the whole body and led to relationships being derived between floc strength and floc size (Tambo & Hozumi, 1979).

However, although jar tests are useful in establishing floc formation, settling rates and densities of the flocs, they are of limited use in quantifying the actual strength and re-attachment ability of the flocs. Floc strength is a difficult property to assess, and there are several theories to suggest which conditions promote stronger flocs. One method of measuring the strength of flocs has been developed by Yeung and Pelton (1996), who used a technique to pull apart individual flocs and in doing so, contradicted some earlier theories that in fact there is no scaling relationship between floc strength and floc size. This has important implications when considering water temperature variations, as larger flocs tend to form in warmer water, but these will not necessarily
be stronger. The same authors later added to this theory by suggesting that floc strength actually depends on the shear rate in which the flocs were formed, and that conditions for optimum flocculation did not coincide with those for maximum shear strength (Yeung et al., 1997). Similar results were found by Dyer and Manning (1999), who found that small flocs were, on average, of higher density than large ones and as such were stronger. This is because there are more points of contact between the particles when they are densely packed.

Another method, more advanced than the jar test, for studying floc formation and re-growth following break up is the photometric dispersion analyser, PDA (PDA 2000 Rank Brothers, Cambridge). This gives signals corresponding to fluctuations in transmitted light intensity as a sample passes through a clear tube. From this, estimations of floc size and development ratios can be derived (Gregory, 1999). This method is very useful as it can graphically display floc formation under a range of influent conditions, i.e. coagulant type, water temperature and chemistry, existing particle content and shear rate (the sample is usually taken from a vessel which is mechanically stirred, similar to the standard jar test). The benefit of studying the latter variable with regard to this research is that data can be produced to illustrate floc behaviour under increased shear conditions (thus simulating a flow change), and the amount of re-growth can be seen following such action.

This has been extensively studied by several workers (See for example Gregory et al. 2000, Yukselen and Gregory, 2002 (a)&(b)) and the experiments have used a range of metal coagulants and polyelectrolytes. In these experiments, floc formation and break up was observed during an initial rapid mixing period, a certain period of slow stir, followed by varying periods of rapid stirring. Collectively, the results have shown
that approximately 10 seconds of initial rapid mixing is the optimum time to promote floc growth during the slow stir phase. The results also show that once the shearing rate was increased, the flocs broke up, and the duration of the rapid stirring largely influenced the floc recovery once the shear rate had been reduced.

It has been found that metal hydroxide flocs tend to form more quickly than those with polyelectrolytes, but that once formed, the polyelectrolyte flocs are far larger. Finally, polyelectrolyte flocs reform to a far higher degree once the period of rapid stirring has ended. Metal coagulant flocs once broken, are irreversibly damaged and only a very limited amount of re-growth is observed. The reasons for this as yet remain unclear, as the breaking action is of a physical rather than chemical nature (Gregory & Yukselen 2002(a) & (b)).

All of these experiments have been at laboratory scale, but a recent study by Rossi et al. (2002) used the PDA 2000 at a full-scale plant in Florence, Italy. The results showed that the PDA is very well suited to optimising coagulant dosing using real influent waters (namely Arno river water), and that the machine was up to 20 times faster in finding the optimal parameters than the standard jar test.

2.7: Effects of water temperature

Several of the investigations into coagulation and in particular floc strength have suggested that there are several external parameters that can affect flocculation, one of which is the influent temperature. The water temperature directly affects the viscosity and an increase in viscosity has been reported to hinder coagulation and sedimentation (Exall and Vanloon, 2000).
PDA 2000 experiments can be repeated using water of differing temperatures, so further investigations can be made into the theory that floc strength is independent of size, and that water temperature is important to the overall effectiveness of the flocculation and filtration processes. Temperature effects have been previously studied by Hanson & Cleasby (1990), who examined the turbine properties and coagulant types necessary to overcome flocculation differences caused by varying water temperatures. They found that colder water temperatures produced smaller flocs and that there was a far longer lag time for the flocs to develop. This has implications for direct filtration, as the influent water may reach the filters before sufficient flocculation takes place. Also, if the media beds themselves are not sufficiently deep, there is an increased risk of breakthrough from non flocculated particles. The alum flocs at low temperatures were also very vulnerable to break up due to fluid shear, and that even the weakest ferric floc was stronger than the strongest alum floc (Hanson & Cleasby, 1990).

Matsui et al. (1998) conducted PDA 2000 experiments to assess the performance of both alum and PACl at different temperatures, and the results complimented the previous researchers. They found that alum was slow to flocculate at lower temperatures and PACl was largely unaffected. However they concluded that the poor performance of alum at low temperatures could largely be overcome by maintaining a constant G value, i.e. increasing the stirring rate for flocculation as the temperature drops. Another way of overcoming temperature differences is to maintain a constant pOH, and to alter the pH. Therefore at 20°C, if the optimum coagulation pH is 7.0, at 5°C it should be 7.6.
All of the previous researchers have come to similar conclusions concerning the poor performance of alum at lower temperatures, and the only variations are between the reasons behind this phenomena. Reduced floc density and aggregate size have also been cited as contributing factors to this poor performance (Morris and Knocke, 1984).

2.8: Effects of flow rate changes

The general effects of flow rate changes have been reported in many papers, dating as far back as Baylis (1958), and Cleasby (1960). It is a phenomenon that has caused increasing concern due to the recently occurring Cryptosporidium outbreaks and despite the published literature on the matter, no quantitative research has been carried out to establish safe parameters for filter operation.

It is well established that changes in flow rates are inadvisable during filtration as these changes cause a decrease in effluent quality and so indicate higher breakthrough levels. Backwashing at water treatment plants will produce some rate changes within the remaining filters, the percentage of which will depend on the numbers of filters at the plant. The varying demand for water at the plant will also introduce rate changes.

One of the founding research papers on this subject was written by Cleasby et al. (1963). They produced the first real experiments to analyse the effects of flow rate changes of varying magnitude, duration and acceleration on effluent quality. The experiments used a single media, sand, with a uniform grain size. Two influent suspensions were used, one containing hydrous ferric oxide, and the other containing hydrous ferric oxide precipitated in the presence of a copper catalyst. 36 runs were performed at flow rate changes of between 10 – 100% and the effluent turbidity was measured to indicate breakthrough.
Several conclusions could be drawn from their work, firstly that larger rate changes caused a larger decline in effluent quality than smaller rate changes. Secondly rapid changes caused more breakthrough than if the same magnitude of rate change had been gradually reached. Thirdly, and perhaps more surprisingly, breakthrough quantities i.e. the amount of shedding above base levels, were virtually independent of rate change duration. In all cases however, effluent quality improved to original levels within 1 hour of the disturbance.

Finally, the type of influent suspension affected the effluent quality. They found that the influent containing the copper catalyst passed 50 times more iron through the filter than the same quantities of the copper free influent. This may be important with reference to today’s Cryptosporidium concerns, and so it is important to establish the influent types and grain sizes which have a higher tendency for breakthrough.

The paper hinted at the changes in shear forces, which occur when the water flow is altered, which move previously attached particles into suspension and ultimately into the effluent water. However, at the time of writing this paper, techniques for particle viewing and further analysis such as video endoscopy were not available. Although this paper has now been superseded by those using more advanced technical equipment, it still illustrates the basic effects of flow rate changes and provides a sound base to expand upon.

One avenue not explored in Cleasby’s paper was the effect of more than one flow rate change in any one filter run. The other extreme to this is to analyse surges, which Baylis (1958) defined as momentary erratic fluctuations in the rate of flow through gravity filters. They were found to be a result of turbulence due to flow constrictions.
through control valves and the amplitude of the surge was proportional to the square of the filter flow rate. Hudson (1981) later showed that surges of amplitudes between 2 – 10% of the flow rate were common in full scale rapid filters and could originate at any high velocity zone such as a bend in the piping.

Glasgow and Wheatley (1998) further examined the effects of surges on rapid gravity filters. Their objectives were not only to confirm whether surges significantly alter filtrate quality, but also to identify how surges influence filter run development. After establishing that surges still occur at plant scale by taking measurements at a local water treatment works, controlled experiments were carried out through two identical filters containing sand and graded gravel. Turbidity again was recorded as a measure of effluent quality. Attached to one filter was a motor driven pump designed to produce pressure fluctuations similar to those observed at a full-scale plant.

PVC powder was used in the influent water as it disperses and forms a stable suspension. The surges applied to filter 2 were kept at a constant amplitude and frequency so as to produce a well-controlled experiment.

The conclusions drawn from this experiment were that surging resulted in poorer initial removal efficiency and a lower rate of head loss development. This inhibited filter ripening as the fluctuations in shear forces within the filter reduced the initial attachment rate of the PVC. However, by the end of the filter runs, similar removal rates and head loss development to the control run were observed.

Overall it was suggested that surging might significantly affect full-scale filter performance. This may only be true of rapid gravity filters, as Timms et al. (1995) observed in experiments with slow sand filters that increasing the flow rate from
0.3m/h to 0.4m/h had no effect on the oocyst concentrations held in the filter and that full scale operations may not lead to any breakthrough. However no mention was made as to the rate of the flow change, i.e. how sudden the change was.

Recent work on flow rate changes has been carried out by Fitzpatrick et al. (1999). Plants were observed in both the UK and USA. Unlike previous researchers, they used particle counters to analyse the filtrate quality. Results showed that peaks in particle counts perfectly corresponded to flow rate increases for all size ranges. They suggest that further research is required to examine the effects of floc strength and other parameters to establish safe levels of operation for a particular type of plant.

It is clear from these researchers that flow rates and flow rate changes have a large influence on the efficiency of a filter, and that very little work has been carried out to investigate the effects of the flow changes themselves. Work is required to further quantify these effects, relying not only on turbidity and head loss, but using particle counting methods which will be discussed in chapter 2.10.

2.9: Viewing Techniques

Traditionally filtration efficiency was, and to a large extent still is, measured by effluent turbidity and head loss. This is a good indicator of overall performance, however, it can mask individual readings, especially when concerned with the breakthrough of a certain particle size. For this reason, other techniques are required to analyse the particles both inside the filter and also in the effluent.
A technique has been developed at University College London, (UCL), using video endoscopy, and was first reported by Fourie and Ives (1982) and then Clough and Ives (1986). This allowed observations to be made from within the filter itself, rather than the limited view of the filter edge that was previously accessible. This produced some results which had not been reported on before.

Endoscopes are rigid tubes going into the filter, viewed usually by camera through a series of lenses to a tip which is illuminated by fibre optics. The diameter of the endoscope most commonly used is 8mm. (Smaller ones are available, but at the time of the experiments by Ives and Fitzpatrick (1989), they were unable to transmit sufficient light to the tip for adequate viewing). This size of endoscope will view an area of approximately 10 sand grains of diameter 0.56mm.

In experiments reported by Ives (1989), and Ives and Fitzpatrick (1989), a series of fixed brass sleeves were built into the filter to allow the endoscope to be inserted at various points in the filter bed, without disturbing the media grains. The sleeves also aid in the focusing distance for a sharp image (Ives and Fitzpatrick, 1989). In many cases, the glass at the end of the brass sleeve has two pairs of 1mm separation perpendicular lines etched onto the surface. This allows calibration of the optical system.

Once the filter is set up, the images within the filter can be viewed in a number of ways. Conventional 35mm or digital cameras can be used to produce static images of filter deposition. These images were illustrated by Ives (1989). He also used a video recorder at the end of the endoscope to observe actual particle motion. His experiments found that anthracite was an unsuitable media for video endoscopy as the grains gave too much light reflection for processes to be observed. Equally
unsuccessful was the use of ferric hydroxide as a coagulant, as the flocs were of a light brown colour and did not provide a significant contrast to the sand grains. He concluded that endoscopy has confirmed many filtration theories concerning particulate deposition and subsequent detachment by the addition of other particles onto the grain. Although probes create their own problems within the filter, i.e. the occurrence of lenticular voids 2 – 3 grains in thickness under the probe itself, these are not thought to be serious enough to preclude the use of this technique. However, the borescope can trap flocs against the lens surface, if using a curved lens, which sometimes remain during a flow change, thus reducing the effectiveness in viewing floc movement.

These techniques have also been used in the study of backwashing. Ives and Fitzpatrick (1989) progressed to using high-speed video recording which is capable of recording moving objects in colour at up to 400 frames per second. This process requires a 250W metal halide lamp for sufficient light. These images can then be played back at standard speed, slow motion, freeze frame and single frame advance. Suitable software involving an XY co-ordinator allowed spatial distances to be combined with time data to calculate object size and motion statistics. However, the 3D nature of the grain movement creates some difficulties in interpreting the data. The experiments involved filtering a 100mg/l suspension for four hours and then recording the effects of backwashing the filter. These experiments used water wash only, although later work found that high speed recording was also suitable to analyse air bubble activity (Fitzpatrick 1993). The conclusion drawn was that only high-speed recording was suitable to analyse the movement during full fluidisation and that lesser speed should only be used to observe sub fluidisation detachment.
However, endoscopy can only capture movements and processes within the filter. As mentioned previously, beyond the filter, turbidity measurements have been widely used to quantify the effects of breakthrough. Several researchers have recently begun to use particle counting as a method of differentiating between the particle sizes and their concentration in the effluent. This is especially important in light of recent *Cryptosporidium* outbreaks, as the oocysts have a distinct size range of 2-5\(\mu\)m.
2.10: **Particle counting methods**

An increasing number of water treatment plants are using particle counters in conjunction with their existing turbidimeters to give a better overall picture of breakthrough characteristics.

A particle counting device consists of a sensor and a counter. A flow control is required to ensure an even flow through the sample cell. The sensor is usually light activated, i.e. as particles flow through the cell, they block out part of the light. The light intensity is measured by a photodetector which, once calibrated, converts the signal into particle size. This allows concentrations of a particular size to be calculated. Current models can only detect sizes down to 2μm, after which the signals due to particles become indistinguishable from background noise. This apparatus is illustrated in Fig. 2.4.

![Fig. 2.4 Schematic of particle counter operation (UKWIR report, 1999)](image)

There are several types of particle counter, the light obscuration models detailed above are most commonly used in water treatment. Also used as a research tool are...
electrical sensing zone counters (ESZ). These work by passing a current through the electrolyte solution that contains the particles to be counted. As a particle passes through the sensing zone, the volume of the electrolyte reduces, which in turn increases the electrical resistance, and so creates a voltage pulse. The size of the pulse is proportional to the size of the particle (Lines, 1992). Both types of counter have the drawback that particles must pass through the sensor individually in order to be counted accurately. False or oversized counts will be recorded if particles pass through simultaneously. A recent study was carried out to investigate the discrepancies between the different types of counter, and it was found that the ESZ counter was far more accurate in measuring small sized particles (<5μm). This is a critical size in water treatment, and the authors, (Van Gelder et. al. 1999), suggest that before any regulatory standards are brought in using particle counters, the manufacturers should investigate increasing the millivolt sensitivity at the lower size range, so that the plants which already make use of particle count data can be more confident of the results in the 2-5μm range (Van Gelder et. al. 1999). However, this does not detract from the overall benefits of using particle counters in water treatment to achieve a more detailed view of the particle size distribution of filter effluent.

LeChevallier et al. (1991) examined the relationship between particle count reduction and Cryptosporidium removal. The experiments analysed the concentrations of naturally occurring oocysts through 4 full-scale plants. The results showed a strong correlation between a reduction in >5μm particle counts and the concentration of Cryptosporidium oocysts.
LeChevallier and Norton (1995) reported on a five-year study at 63 surface water sites in Mid West USA. Particle counters were used to provide Cryptosporidium concentrations in raw and settled water, individual filter effluents and the combined plant effluent. The result of particle count reduction corresponding to Cryptosporidium removal was observed in all plants where Cryptosporidium originated in the raw water. A ratio of log\textsubscript{10} reduction in particle counts to log\textsubscript{10} reduction in Cryptosporidium levels was developed to further analyse this relationship. Theoretically, if both reductions correspond exactly, the ratio would be 1.0. The results showed 70% of the samples ranged between 0.8 and 1.6 (mean =1.2). However, it must be remembered that the difference between influent and effluent counts does not take into account processes within the filter, for example flocs may aggregate smaller particles together into Cryptosporidium sizes, thus skewing the results.

Also observed in the experiments was the effect of coagulation, better removal was observed for waters with higher initial particle counts.

This research confirmed that particle counting is an accurate method of assessing Cryptosporidium removal, although research carried out by Morse et al. (2001) and Wilson and Morse (2002) disputed this. They found that Cryptosporidium counts correlated with neither filtered particle counts or turbidity readings. The counts also showed no relationship between those in the raw and filtered water, i.e. high raw water counts did not necessarily correspond to high filtrate counts, but also high filtrate counts could not always be explained by a previously high raw water count. This research suggests that incidents of Cryptosporidium breakthrough can be
independent of any other factor, and that to be safe, the whole filter operation must be optimised as much as possible.

The relationship between particle counts and turbidity is not straightforward. Hall and Croll (1997) carried out plant scale experiments to analyse the risk of Cryptosporidium breakthrough in rapid gravity filters and also to compare the two methods of measuring effluent quality. Cryptosporidium oocysts were dosed into water extracted from the River Thames. Filtration through a variety of media followed chemical coagulation and flocculation. Results showed high levels of turbidity and particle counts at the start of the run, which corresponded with the higher concentration of oocysts during the first hour. This indicates that particle breakthrough is a good indication of Cryptosporidium risk. It was calculated that 30% of all breakthrough occurred during this initial peak but when slow start up procedures were adopted, this was greatly reduced.

It was also concluded that although there was some correlation between particle counts and turbidity, comparing peak values revealed no match at all, for example start up turbidity peaks of between 0.1 NTU and 0.3 NTU were associated with particle counts of between 1000 and 15000/ml. This is also highlighted in results of 2 full scale plants which had similar turbidities of 0.1 – 0.2 NTU at both sites but 2 - 5μm particle counts of 20 – 250/ml at one site and 2000 – 6000/ml at the other. This indicates a serious flaw in the use of turbidity measurements for predicting Cryptosporidium risk.
In a report from the UK Water Industry Research (UKWIR) (1999) an analysis was made of the performance of 3 types of particle counters and 2 types of turbidimeters. Five filters ran in parallel and were all supplied with the same influent water. The results confirmed that particle counters are more sensitive to water quality changes than turbidimeters.

The results between the three particle counters were very similar and so the choice should be made according to the individual requirements of the experiment. For example the HIAC particle counter is the most portable but needs regular downloading of information so is more suited to smaller scale experiments. However, several reports have stated that turbidimeters are far better at detecting sub-micron particles, and that the main flaw in particle counters is that they are only capable of measuring particles down to 2μm in size. (Bayley and Chipps 2001, Sadar, 2001). For this reason, they are ideal to complement each other to provide a complete picture of particle breakthrough.

Although several researchers are undecided as to the benefit of particle counters as anything other than a research tool (Roder, 2000, Bayley & Chipps, 2001), the fact remains that they are hugely beneficial in determining the particle size distribution of filter breakthrough. As long as they are benchmarked to the site specific conditions, they can help to optimise the filtration efficiency (Roder, 2000).

Water companies and regulatory bodies are continually striving to provide safer drinking water and more stringent standards are being imposed. In the US, regulations state that water must be 0.3NTU for 95% of the time, but a voluntary partnership now utilises 0.1NTU as their target performance (Pontius, 2001).
Due to the limitations with current turbidimeters (e.g. the broad wavelength and unstable nature of the tungsten light source), a new machine has been developed to read confidently far lower turbidity values.

The Filtertrak 660 Laser nephelometer uses a laser diode with a wavelength of 660nm instead of the tungsten bulb. This light beam has a relatively high beam power density and so results in a higher scattered light intensity from smaller particles. This is capable of detecting turbidity changes as little as 0.005NTU, which would only be recorded as “noise” on traditional turbidimeters. It enables detection of periods of poor effluent quality far earlier than either turbidimeters or particle counters, before the water quality has reduced to unacceptable levels in terms of regulatory standards (Sadar, 2001).

This instrument has been trialled at several WTW’s, and results have been very positive. It has been found that the Filtertrak has similar performance to particle counters, but that it recorded far longer ripening periods (up to 6 hours in some cases) during full scale filter runs. This is thought to be due partly to the slow settling nature of sub micron particles, and partly because the filter takes so long to optimise to these sized particles. End of run breakthrough was also recorded up to 2h earlier than for the particle counters (Sadar, 2001, Carlson & Johnson 2001). It has also been noted in previous studies that breakthrough events that were only picked up on the Filtertrak were often a pre-cursor to larger breakthrough events that were then recorded on the particle counters and standard turbidimeters (Sadar, 2000, Johnson et al., 2000).

The machine is not yet approved by the EPA in the USA for recording purposes but early indications suggest that this will be a valuable tool in analysing sub-micron
particle breakthrough (Johnson et al. 2000). However, this will not create an additional benefit when considering Cryptosporidium breakthrough, as the oocysts are large enough to be recorded on conventional monitors.

2.11: Cryptosporidium

Cryptosporidium is an intestinal parasite causing vomiting and diarrhoea. The symptoms of Cryptosporidiosis usually last 10 -14 days and it is more common in children and those with immuno-deficiency diseases such as AIDS. In these people, the infection can be very serious as it is not self-limiting. It is transported largely through animal and cattle faeces entering water systems. Outside of the host, the parasite Cryptosporidium parvum travels as oocysts measuring 3 -5μm in diameter. In this state, Cryptosporidium is virtually immune to chlorination, which is a widely used disinfectant processes within water treatment plants. In recent years Cryptosporidium outbreaks such as Milwaukee in 1993 in which approximately 370 000 were infected (Davis, 1993), and North London in 1994 have highlighted the need for effective water filtration and have raised concerns about current filtration practices (Ongerth and Pecoraro, 1995).

As oocysts are so resistant to other forms of treatment, direct filtration must remove them from the supply before disinfection takes place. There have been several studies on the effectiveness of various filtration methods. Timms et al. (1995) reported on the effects of slow sand filtration on Cryptosporidium, as slow sand filtration is employed at 6 plants in London which supply surface derived water (which has a higher chance of becoming contaminated as it is exposed to animals and sewage). An
experiment was carried out at the Surbiton water treatment works. Oocysts were inactivated by heating at 60°C for 15 minutes and then mixed with the raw water to give a concentration of 4000 /l. This was then slow filtered through sand and gravel. The results were a 99.997% reduction in oocyst concentration with all oocysts being trapped in the top 2.5cm of the filter. This would indicate that slow sand filters are very successful in removing Cryptosporidium. However, this only accounts for one type of filter and as rapid gravity filters are more common in water treatment, research was required to investigate the success rate of this type of filter.

Ongerth and Pecoraro (1995) conducted experiments using multimedia gravity filters. Owing to the fact that Cryptosporidium oocysts are similar in surface charge and settling characteristics to Giardia cysts (although the cysts are slightly larger in size, 5-10μm), the experiment was set to the same parameters as previous Giardia experiments reported in other literature, so that comparisons could be made. The media used in these experiments were anthracite coal, silica sand, garnet and three grades of gravel together as one multi media filter. These were pre-washed and backwashed to ensure all fines were eliminated. Separate runs were performed at various coagulation levels to analyse the importance of chemical coagulation. Results showed between 2.7 and 3.1 log Cryptosporidium removal, i.e. an average reduction of 5000/l to 5/l. However, when coagulation levels were not at their optimum, removals dropped to only 1.5 logs, indicating that coagulation is an important process in Cryptosporidium removal.

Effluent readings were only taken after filter ripening, and so turbidity levels had stabilised at <0.05 NTU. This may have altered the overall results as previous
literature has suggested that Cryptosporidium breakthrough may be high during the initial start up period of the filter run.

Similar results have been reported by Emelko *et al.* (1999) who achieved greater than 4 log oocyst removal during stable coagulant conditions which then dropped to 2 log removal during coagulant failure.

Hall *et al.* (1995) reported further on the effects of chemical coagulation. Their experiments encompassed a wide range of conditions, analysing different filter media, varying flow rates and two types of coagulant in Dissolved Air Flotation (DAF). Jar tests were performed to establish optimum coagulation conditions. Alum was observed to be the most effective in oocyst removal. Comprehensive results were achieved, showing DAF filtration removal of between 99.33 – 99.98%, allowing for recovery-efficiency in Cryptosporidium techniques (Hall *et al.*, 1995).

Even throughout a failure of the DAF unit, which allowed flocculated water to pass directly to the filters, oocyst concentrations remained at non-detectable levels. In this experiment, unlike that of Ongerth and Pecoraro (1995), concentrations were measured during the filter start up, and results indicated that turbidity levels were higher during this initial phase, which may lead in an increased risk of oocyst breakthrough, although no significant results were obtained to confirm this. The authors recommend a slow start up procedure to limit these risks.

A change in filtration rates during this experiment from 5m/h to 10m/h caused a wider range in turbidity readings and oocyst concentrations rose from being undetectable to having low concentrations. This is an area that requires further research.
Another method of reducing *Cryptosporidium* breakthrough has been investigated by Shaw *et al.* (2000). The negative electrical charge on the sand media was corrected by coating the grains with hydrous iron aluminium oxide. This increased the zeta potential from $-40\text{mV}$ to $+45\text{mV}$ and so enhanced the potential for capturing the negatively charged oocysts. Results showed a significant improvement in oocyst removal, even during periods of sub-optimal coagulation. Also, as the media is coated and dried prior to use, the coating was not removed during the first backwash. At this time however, the lifespan of the media coating is not yet known and once installed in the filters, to remove and re-coat the media could be costly.

An interesting paper written by Craft (1993) examined Wessex Water's practice of reusing backwash water, so as to conserve valuable water resources. This has serious implications as it has been highlighted that backwash water has the potential for high concentrations of *Cryptosporidium* oocysts, ultimately increasing the risk of breakthrough. To overcome this problem, experiments were carried out to filter the backwash water through a Fibrotex filter, prior to release into the reservoir. This filter achieved 99.9% removal efficiency for *Cryptosporidium* sized particles and since commissioning the filter, no *Cryptosporidium* had been detected in the water supply (Craft, 1993).

Whilst all of these pilot studies have actively monitored the water for oocyst concentrations, full-scale sampling is not as effective. Clancy and Fricker, (1998) stated that most plants monitor effluent on a monthly basis, taking a sample of less than 100 litres. This means that for large plants such as that in Las Vegas, which produces 1500MI/d, the results become unrealistic.

This has partly been remedied in the UK because in 1999 the Drinking Water Inspectorate, (DWI), were given stronger powers to enforce new legislation whereby
water must not contain more that 1 oocyst per 10 litres and high risk plants are to sample and analyse the water daily (Odell, 2000).

Despite this, Klonicki et al. (1997) made the point that very few research experiments consider the Cryptosporidium oocyst characteristics themselves and by poor oocyst selection and varying counting techniques, results may be inaccurate or misleading. They carried out experiments to compare different counting techniques and discovered wide discrepancies between them. Although offering no distinct conclusion or recommendations, the paper has highlighted the complexities and problems with dealing with Cryptosporidium and the need for repeat measurements using oocysts within narrow characteristic parameters.

However, work currently being carried out by Emelko et al. (2001) has found a suitable alternative. They have examined the breakthrough characteristics of both oocysts and polystyrene microspheres during optimal and challenged filtration. The work was carried out at two pilot plants and the columns were dosed with both the inactivated oocysts and fluorescent microspheres. Sampling was taken during stable operation and also during periods of higher turbidity. The results have shown that firstly once the turbidity rises to just 0.3NTU, the log removal of both oocysts and microspheres reduced from >5 to 1.5. Secondly, the oocysts and microspheres have almost identical removal amounts for all conditions. This makes the microspheres an excellent surrogate for Cryptosporidium, without the disadvantages of the oocysts themselves. The benefits of microsphere surrogates have been confirmed by studies carried out by Swertfeger et. al. (1999), who found that the removal rates of the microspheres correlated to actual oocyst removal far more closely than turbidity or particle count readings.
The latest developments may also help address these counting difficulties. Genera Technologies Ltd. designed a device to capture parasites. The ‘Filta-Max’ has recently been endorsed by the DWI, and this is the first stage of a three fold process which may revolutionise parasite recovery.

Once the particles have been trapped by the filter, the parasites must be retained whilst the remaining particles are removed. This is done using the ‘Puri-Max’ which uses a plate of paramagnetic beads coated with a *Cryptosporidium* antibody to trap only the parasites. A phosphorescent dye used in other counting methods can then be introduced before the final stage of identification and quantification. ‘Quanti-Max’ is a semi-automated process which involves mounting the parasites on a glass slide and scanning them before being displayed on a monitor. This eliminates the potential for missing individual oocysts, which was a problem with previous manual microscope counting. This technique requires less staff time and can handle far larger data sets (Odell, 2000). This technology is now being used by Severn Trent Water Ltd and is proving to be successful and accurate (Morse *et al.* 2001).

Although it is widely acknowledged that chlorination is ineffective for oocyst inactivation, there are several studies which have recently looked into other methods of inactivation, such as Finch *et al.* (1997), who applied chemicals sequentially rather than individually during the disinfection process. The chemicals used include ozone, monochloramine and free chlorine. At an optimum pH level of 6.0, the use of chlorine dioxide and ozone produced a 4 log inactivation of the oocysts.
UV light is also being tested and Clancy et al. (1998) have conducted field trials in Wisconsin which have provided results showing over 4 log inactivation of *Cryptosporidium* oocysts.

These disinfection processes provide encouraging results for the effective control of *Cryptosporidium*, although the costs may still potentially outweigh the benefits.

### 2.12: Filtration Modelling

There have been several models and computer simulations to predict filter behaviour, focusing on processes such as backwashing and headloss development. One of particular importance for this research is Stevenson’s (1997a,b,) Multiple Flexible Layer Model, Filterflex. This aims to predict particle breakthrough during filtration and can incorporate many “real life” situations such as flow rate changes into the model.

It is based upon the theory that filter media are not actually homogenous and so uses 5 grain size fractions, which then requires 5 different void dimensions. The suspension also contains 5 size fractions, thus making it more realistic. The model is designed to deposit or remove solids from each void, depending on the shear stress. When the shear stress value is exceeded, the solid is removed from that particular void and is incorporated into the suspension moving down to the next depth increment.

There are several variables which can be programmed into the model to suit the required filter conditions. These include the depth and grain size of the media, the flow rates, and also the physical conditions of the influent suspension, i.e. viscosity, density and the floc size and concentration.
The model appears to be able to realistically simulate many occurrences, such as wormholes (channels free from deposits which run deep into the bed), and an increase in breakthrough during flow rate increases.
2.13: Summary

The accumulation of the information in the published literature has provided an excellent background for the current research. It is clear how many processes are involved in producing high quality potable water, and that each and every process must be optimised in order for the water treatment system to be efficient. For example, even if the media configuration is suitable for the filter dimensions and flow regime, without correct coagulation, the filter as a whole will be ineffective. The threat of an outbreak of Cryptosporidiosis ensures that water quality standards are becoming increasingly stringent, and the technology to accurately monitor the effluent quality is becoming more available and efficient. It has been demonstrated by several researchers (refer to section 2.10) that particle counters are very effective for recording the number and size distribution of particles in the effluent. Other methods of analysing filter behaviour include the use of video endoscopy, to view the detachment and media grain behaviour within the filter, and computer simulations to predict how a filter may behave under certain conditions.

All of this information has been useful to identify and explain factors which improve filter efficiency, and also where there is a limited area of research. One area in particular is the actual filter performance under different flow conditions, and this current research should provide a better understanding as to why flow changes cause increased particle breakthrough. The research detailed in this chapter provides an information base begin this research, for example the use of common media types, backwashing regimes and coagulant dosing. This research can also be used to assess the suitability of particular computer models for predicting filter behaviour.
3 METHODOLOGY

This chapter details the methods used to conduct the laboratory experiments, as there were many factors to consider when constructing and operating the filter column. The processes that are described in more detail include the physical dimensions of the apparatus, the flow and backwashing regimes, the coagulant dosing, and the processes involved in recording and viewing the particle breakthrough. It provides a comprehensive review of how the experiments were conducted.

3.1 Filter column apparatus

The laboratory experiments used a Perspex column which was 2m in height and 0.166m internal diameter. The base of the column was conical in shape and contained ballotini (glass spheres with a diameter of approximately 2cm). This not only supported the media but also dispersed the backwash flow of water and air, thus eliminating the need for a supporting layer of gravel. A wire mesh separated the media and ballotini so that no sand was lost from the column during normal filtration. Inserted into the bottom half of the column were five ports for video recording purposes, six manometer ports and five sampling ports to enable testing of the water at various depths of the filter bed. At the top of the column were two outlets for backwash water. This enabled the filter to be backwashed at various bed expansions without the loss of the filter media. All of the above are illustrated in the schematic diagram of the entire apparatus, Figure 3.1.
Figure 3.1 also shows the supply tank, which was fed from the main supply tank for the department of Civil and Environmental Engineering at University College London. The tank had a capacity of 210 litres and was fitted with a ballcock to ensure supply on demand.
Suspended in this tank was a thermostatically controlled water heater. This allowed the influent suspension to pass through the filter at a pre-set temperature, and was installed for the final set of experiments examining the effects of the water temperature on filter efficiency. The kaolin suspension was fed into the tank and the water was pumped up to the constant head tank which supplied the column. The tank was high enough to provide a head of 1.6m onto the media, when the bed depth was 1m.

The coagulant was added just before entering the column via a baffle mechanism which was a flat spiral coil of metal within the tubing. This ensured sufficient mixing energy for flocculation. The mixing time available before reaching the media bed was 12 minutes when the water flow rate was 5 m/h. This direct filtration method was used to avoid coagulant recycling via the constant head overflow. A Hach turbidimeter was used to continuously monitor the turbidity of the suspension in the constant head tank. This enabled visual confirmation that the kaolin was always being dosed at the correct rate.

3.1.1: Data collecting equipment

Once the suspension had passed through the filter, the flow was controlled using a gate valve, and the rate was measured by both a standard rotameter and an electromagnetic flowmeter. This monitored the flow continuously and gave an electrical reading which could be downloaded into a PC software package, Winwedge. This enabled a continuous flow measurement to be made and meant that
any unintentional changes in flow could be recorded during the night or when the column was unattended.

Finally, once the flow had been measured, a small amount of flow was diverted into the particle counter. This was a Met One particle counter, model WGS26, and was capable of reading particles in the range 2-15μm, in 6 separate size channels. These channels were 2-3μm, 3-5μm, 5-7μm, 7-10μm, 10-15μm and those particles larger than 15μm. Midway through the laboratory experiments, a new particle counter was purchased and was identical to the existing one. In comparative trials, the new particle counter provided similar particle count data to the existing instrument, providing evidence to suggest that the previous particle count data would still be valid.

3.2: Media Selection

The initial experiments were conducted using Leighton Buzzard sand of grain size 0.5 – 1.0mm, as it is commonly used in filters for potable water applications. To ensure that the grading stated on the bag was accurate, three samples of 200g were taken from various sections of the bag and sieved for 20 minutes through a sieve set of 1200μm -500μm. Table 3.1 below details the fraction weights.

<table>
<thead>
<tr>
<th>SIEVE SIZE</th>
<th>WEIGHT (g)</th>
<th>%</th>
<th>CUMULATIVE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;500μm</td>
<td>0.9</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>500μm</td>
<td>16.0</td>
<td>8.15</td>
<td>8.61</td>
</tr>
<tr>
<td>600μm</td>
<td>105.6</td>
<td>53.77</td>
<td>62.38</td>
</tr>
<tr>
<td>710μm</td>
<td>58.4</td>
<td>29.73</td>
<td>92.11</td>
</tr>
<tr>
<td>850μm</td>
<td>13.4</td>
<td>6.82</td>
<td>98.93</td>
</tr>
<tr>
<td>1000μm</td>
<td>1.8</td>
<td>0.92</td>
<td>99.85</td>
</tr>
<tr>
<td>1200μm</td>
<td>0.3</td>
<td>0.15</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3.1: Sand fraction weights
Figure 3.2 is a cumulative percentage curve of the average fraction weights. This graph is used to calculate the uniformity coefficient which is a measure of dispersion. The value is obtained by dividing the size of sand grains which are smaller than 60% of the total \((d_{60})\) by the size of grains which are smaller than 10% of the total \((d_{10})\).

In this case, that figure becomes

\[
\frac{d_{60}}{d_{10}} = \frac{708}{605} = 1.17
\]

The data can also be used to calculate the hydraulic size of the sand \((d_n)\). This can then be put into other theoretical equations which require the grain diameter.

To calculate hydraulic size, the percentage retained on each sieve must be divided by the corresponding sieve size. These values must be totalled and divided by 100. The
reciprocal of this value is obtained and finally, 10% of the reciprocal value is added to adjust for the fact that the sieves are set at 20% size increments. Table 1.2 gives the values obtained for the media used. A nominal value of 0.499mm was given for the pan size, although technically this incorporates all sizes less than 0.500mm.

<table>
<thead>
<tr>
<th>SIEVE SIZE (MM)</th>
<th>%</th>
<th>% / SIEVE SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.499</td>
<td>0.46</td>
<td>0.92</td>
</tr>
<tr>
<td>0.500</td>
<td>8.15</td>
<td>16.3</td>
</tr>
<tr>
<td>0.600</td>
<td>53.77</td>
<td>89.62</td>
</tr>
<tr>
<td>0.710</td>
<td>29.73</td>
<td>41.87</td>
</tr>
<tr>
<td>0.850</td>
<td>6.82</td>
<td>8.02</td>
</tr>
<tr>
<td>1.0</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>1.2</td>
<td>0.15</td>
<td>0.125</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>157.78</strong></td>
</tr>
<tr>
<td><strong>DIVIDE BY 100 = 1.578</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RECI PROCAL = 0.63</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ADD 10%</strong></td>
<td></td>
<td><strong>0.70MM</strong></td>
</tr>
</tbody>
</table>

Table 3.2: Hydraulic grain size (d_p)

3.2.1: Headloss measurements

Having obtained the hydraulic grain size, as previously mentioned, this can be used in several theoretical calculations. One of which is headloss measurements.

Headloss is calculated using the Kozeny-Carman equation, which is:

\[
\frac{H}{L} = \frac{5 \mu v (1-\varepsilon)^2}{\rho g \varepsilon^3 \left(\frac{6}{d}\right)^2}
\]

Where \( H = \text{Headloss through sand bed, m} \)
\( \mu = \text{Dynamic viscosity of water, Nsm}^{-2} \)
\( \rho = \text{Water density, kgm}^{-3} \)
\( v = \text{Approach velocity, m}^{-1} \)
\( \varepsilon = \text{Porosity of bed} \)
\( g = \text{Acceleration due to gravity m}^{-2} \)
\( d = \text{Grain diameter, m} \)
Both the absolute viscosity and the fluid density are temperature dependent and so different headloss values will be achieved for different water temperatures.

At 20°C, with a flow rate of 5m/h, the headloss through the column for a 1m bed is:

\[
H = \frac{5 \times 1.0087 \times 10^{-3}}{998.23} \times 0.00139 (1 - 0.4)^2 \left( \frac{6}{0.0007} \right)^2
\]

\[
H = 0.296m
\]

This is the value for a clean bed and correlates very well with that found in practice, which ranged from 0.22m to 0.28m. These variations may be due to water temperature differences or changes in the initial bed consolidation.

As the experiments were conducted at different starting flow rates, and also at varying water temperatures, the clean bed headloss for these variables was also calculated. These are displayed in the table below.

<table>
<thead>
<tr>
<th>FLOW RATE m/h</th>
<th>15°C</th>
<th>20°C</th>
<th>25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.336</td>
<td>0.296</td>
<td>0.263</td>
</tr>
<tr>
<td>6.25</td>
<td>0.42</td>
<td>0.369</td>
<td>0.328</td>
</tr>
<tr>
<td>7.5</td>
<td>0.502</td>
<td>0.442</td>
<td>0.393</td>
</tr>
<tr>
<td>10</td>
<td>0.671</td>
<td>0.591</td>
<td>0.525</td>
</tr>
</tbody>
</table>

Table 3.3: Clean bed headloss values

Once the media had been selected and sieved, it was dried for 12 hours at 150°C to eliminate any moisture. The sand was also weighed before being put into the column.

For a bed depth of 1m, and with the column area of 0.0216m², the amount of sand required was 34.50kg. This allowed for medium compaction of the bed to achieve a 1m depth.
Having established the total weight of the sand in the column, the porosity could be calculated, which would subsequently be required for backwashing fluidisation calculations. The porosity equation is as follows:

\[
\text{Porosity} = \frac{\text{pore volume}}{\text{bed volume}} = \frac{\text{bed volume} - \text{solid volume}}{\text{bed volume}} = \frac{\text{bed volume} - \frac{\text{mass}}{\text{density}}}{(1m \cdot \pi \cdot 0.083^2)} = \frac{(0.0216 - 34.5/2650)}{0.0216} = 0.40
\]

As not all treatment plants use a standard depth of filter media, it was necessary to repeat some of the experiments on a reduced bed depth. This would give an idea of how critical bed depth is in determining the efficiency of the filter. The sand was siphoned out of the top of the column, to leave a bed depth of 0.6m. As the media had backwashed using collapse pulsing prior to being removed, the media was sufficiently mixed, and sieve analysis of the removed material showed that the size distribution of the media was very similar to the initial range. Experiments were then carried out, keeping all of the other variables identical, so as to isolate the effects of the media depth itself.

After completing work at several treatment plants which used dual media (sand/anthracite) filtration, the decision was made to recreate these conditions in the laboratory. Anthracite of grain size 1.18-2.36mm was used to create the bed configuration 0.5m sand (0.5-1.0mm grain size) + 0.3m anthracite. The anthracite was the same grade as that used in the full size treatment plants studied. It was
obtained from the same supplier as Paterson Candy, as they request a very specific size range. This meant it was unnecessary to manually grade the anthracite once it arrived, and a detailed specification sheet was provided (see appendix 2). Once the media had been placed in the column, the filter was vigorously backwashed to remove any remaining fines. The backwashing regime for the experimental work had to be altered to accommodate the less dense nature of the anthracite, and this is discussed in more detail in the section 4.4.

3.3: Influent water properties

All of the laboratory experiments were conducted using London tap water, which has an average pH of 7.8, average conductivity of 0.4mS/cm and a temperature range of 13-26°C in the laboratory.

Kaolin light (China Clay) was added to the supply tank at such a rate so that the influent water into the filter contained 50mg per litre of kaolin for the 8 hour filter runs and 10mg/l for the 24hr runs. As the runs were of long duration, the kaolin had to be delivered into the supply tank from a highly concentrated solution via a peristaltic pump. The kaolin tank held 40 litres and so the concentration had to be strong enough to be able to supply the total water demand during the filter runs. This would obviously be different for each starting flow rate and run duration, as the total consumption would vary. An example would be that in 8 hours, with the filter running at 5m/hr (1.8l/min), the total water consumption is 864 litres, and so the total kaolin demand is 43.2g. With a kaolin concentration of 8500mg/l in the supply tank, the suspension must be delivered at a rate of 0.64 l/h. The dosing rate for the 10mg/l
suspension was 0.13 l/h. Measuring cylinders and timers were used to establish the pumps provided these rates accurately.

During the flow rate changes, the kaolin delivery rate had to be increased accordingly, e.g. a 100% flow increase on 5m/hr requires a kaolin delivery rate of 1.28 l/h. (at 50mg/l kaolin).

Table 3.4 below details the delivery rates required for each flow rate and subsequent rate changes.

<table>
<thead>
<tr>
<th>INFLUENT KAOLIN SUSPENSION</th>
<th>% FLOW CHANGE</th>
<th>NEW FLOW RATE M/hr + l/min</th>
<th>KAOLIN TANK SUSPENSION mg/l</th>
<th>KAOLIN FLOW RATE l/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mg/l</td>
<td>0</td>
<td>5</td>
<td>1.8</td>
<td>8500</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>6.25</td>
<td>2.25</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>7.5</td>
<td>2.7</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>8.75</td>
<td>3.15</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>10.00</td>
<td>3.6</td>
<td>1.28</td>
</tr>
<tr>
<td>10 mg/l</td>
<td>0</td>
<td>5</td>
<td>1.8</td>
<td>8500</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>6.25</td>
<td>2.25</td>
<td>0.163</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>7.5</td>
<td>2.7</td>
<td>0.195</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>8.75</td>
<td>3.15</td>
<td>0.228</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>10.00</td>
<td>3.60</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 3.4: Kaolin dosing rates

3.3.1: Alum coagulation Jar tests

Initial runs using kaolin alone revealed the need for coagulation, as the particle counts suggested minimal removal. Aluminium sulphate was used initially and jar tests were performed to obtain the optimum dose required for flocculation. Given that the filter was operated as a direct filtration column and so no prior settlement or clarification was carried out, the alum dose which encouraged flocculation but didn’t produce too large flocs was chosen. This prevented the formation of a thick mat forming on the media surface which could lead to surface binding and high filter headloss.
The jar tests involved dosing the alum, rapid stirring for 10 seconds followed by 10 minutes of slow stirring, and finally 15 minutes of settlement. Six 800ml jars of 50mg/l kaolin suspension were tested using amounts of alum in the range of 0-0.4ml. This produced an optimum alum dosing rate of 0.19ml/l (using M/10 alum).

The 24 hour runs required a kaolin suspension of 10mg/l and this was tested using an alum range of 0-0.3 ml. This produced an optimum dosing rate of 0.16ml/l (M/10 alum). The pH of the optimum alum dose was not investigated.

The coagulant was then pumped via a peristaltic pump up to the top of the column itself, to prevent recycling of the suspension via the constant head tank, which may have damaged the flocs. A baffle mechanism within the pipe ensured that the coagulant received enough mixing energy for flocculation before reaching the filter bed itself.

The peristaltic pumps operate more accurately at higher speeds, so to ensure the alum was being dosed at the correct rate, a more dilute solution, M/30, was used. This gave corresponding dosing rate of 0.9ml/min which contained 1.62g of Al.

The peristaltic pumps for both the coagulant and kaolin dosing were frequently calibrated using a measuring cylinder and timer, thus ensuring the correct dosing rates during both stable operation and also flow increases. The tubing was also changed at regular intervals to prevent sediment build up restricting the flow.

The particle size distribution of the kaolin suspension was required before it was used in the filter, so 20mg of light kaolin clay was suspended into 2 litres of deionised water. This was analysed using the particle counter, taking a 5 second sample every 10 seconds for 20 minutes. This was repeated three times and the average counts per
ml for each size range are illustrated in table 3.5. Also included in this table is the particle size distribution of a 2litre London tap water sample, as this was also required to get the base particle readings. The sampling followed the same protocol as the kaolin sample. Both the old and new particle counters were used and recorded.

<table>
<thead>
<tr>
<th>PARTICLE SIZE (μm)</th>
<th>KAOLIN PARTICLE COUNTS PER 100ml</th>
<th>WATER PARTICLE COUNTS PER 100ml</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLD</td>
<td>NEW</td>
</tr>
<tr>
<td>2-3</td>
<td>85.6</td>
<td>101.2</td>
</tr>
<tr>
<td>3-5</td>
<td>734.4</td>
<td>720.1</td>
</tr>
<tr>
<td>5-7</td>
<td>749.7</td>
<td>767.9</td>
</tr>
<tr>
<td>7-10</td>
<td>3477.2</td>
<td>3317.7</td>
</tr>
<tr>
<td>10-15</td>
<td>5751.1</td>
<td>5701.5</td>
</tr>
<tr>
<td>&gt;15</td>
<td>6234.3</td>
<td>6170.0</td>
</tr>
</tbody>
</table>

Table 3.5 Particle size analysis using both old and new particle counters

3.3.2: Temperature effects on Alum

Jar tests were also performed to investigate the effect of temperature on the size and flocculation performance of alum. For improved visibility during the tests, 50mg/l of kaolin was used, and was flocculated with the corresponding optimum dose of alum. Three water temperatures were investigated, 11, 16 and 25°C, as these represented the temperature range observed throughout the year in the laboratory.

In similar fashion to the original jar tests (see section 3.3.1), the samples were stirred rapidly for 10s, followed by 10 minutes of slow stirring and finally 15 minutes of settlement time. At each stage, visual observations and turbidity readings were taken.
### Table 3.6: Floc development using alum at varying water temperatures

<table>
<thead>
<tr>
<th>Initial Visual Observations</th>
<th>25°C</th>
<th>16°C</th>
<th>11°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Minute Turbidity</td>
<td>9.2 NTU</td>
<td>13.2 NTU</td>
<td>18.9 NTU</td>
</tr>
<tr>
<td>10 Minute Visual Observations</td>
<td>Large flocs settle straight away</td>
<td>No settlement of flocs</td>
<td>Pinprick flocs, no settlement.</td>
</tr>
<tr>
<td>15 Minute Turbidity</td>
<td>1.6 NTU</td>
<td>3.3 NTU</td>
<td>3.7 NTU</td>
</tr>
<tr>
<td>Final Water Temperature</td>
<td>25.5</td>
<td>18</td>
<td>15</td>
</tr>
</tbody>
</table>

### 3.3.3: Polyaluminium chloride Coagulant

To investigate the importance of water temperature on filter efficiency further, Polyaluminium Chloride (PACl) was used instead of alum, at a range of water temperatures, as it is reported to be more able to cope with varying temperatures.

As a commercial product from Kemira, Sweden, PAX (a type of PACl) comes in different concentrations of aluminium. It has been found that PAX dosing compares very well to alum if the Al content is the same (Yukselen and Gregory 2002). As the filter runs were of such long duration, the PAX supplied had to be of sufficient Al concentration that it could be effectively dosed into the column. These calculations are based on a kaolin concentration of 10mg/l as the experiments using PAX only used this lower concentration.

The Al content of the alum used is as follows:

\[
\text{Alum} = \text{Al}_2\text{SO}_4 \quad (\text{Molar mass of Al} = 27) \quad \text{So } \frac{M}{30} = \frac{27 \times 2}{30} = 1.8 \text{g of Al per litre}
\]

Dosed at 0.9ml/minute = 1.8*0.9 = 1.62mg of Al per minute.
The PAX supplied had a 5.2% weight as Al, with a density of 1.24g/cm³. Therefore
1ml PAX = 1.24 * 0.052g.

Expressed in milligrams, this becomes 1μl PAX = 0.06448 mg Al.

To equate to the alum dosing in terms of Al content; 1.62mg / 0.6448 mg =
25.12μl/min

No additional jar tests to confirm this optimum dose were performed.

PAX deteriorates in efficiency with time once it has been diluted, only the amount of
solution required for each 24h run was prepared in advance. The PAX was diluted by
a factor of 20 so that there was sufficient solution to be accurately pumped via the
peristaltic pump.

These experiments were conducted using a full 1m bed depth of sand, as a better
comparison to the alum experiments. The experiments were carried out in winter,
when the water temperatures were low (approximately 15°C), so to investigate
summer temperature PAX efficiency, the tank water heater was used to warm the
water to 25°C.

3.3.4: Temperature effects on PAX

Having previously established the effects of the influent water temperature on alum, it
was necessary to repeat the procedure using PAX. Jar tests were performed using the
same protocol (see section 3.3.2). Table 3.7 below details the floc development and
subsequent turbidity of using PAX at different water temperatures.
INITIAL VISUAL OBSERVATIONS

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>Rapid flocculation, large flocs after 2 mins</td>
</tr>
<tr>
<td>16°C</td>
<td>Similar floc development between temperatures, much slower than 25°C, only small flocs after 3 mins</td>
</tr>
<tr>
<td>11°C</td>
<td></td>
</tr>
</tbody>
</table>

10 MINUTE TURBIDITY

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>5.4</td>
</tr>
<tr>
<td>16°C</td>
<td>12.8</td>
</tr>
<tr>
<td>11°C</td>
<td>12.9</td>
</tr>
</tbody>
</table>

10 MINUTE OBSERVATIONS

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>Large flocs show rapid settling</td>
</tr>
<tr>
<td>16°C</td>
<td>Identical looking floc size, very slow settling</td>
</tr>
<tr>
<td>11°C</td>
<td></td>
</tr>
</tbody>
</table>

15 MINUTE TURBIDITY

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>2.2</td>
</tr>
<tr>
<td>16°C</td>
<td>7.5</td>
</tr>
<tr>
<td>11°C</td>
<td>7.6</td>
</tr>
</tbody>
</table>

FINAL TEMPERATURE

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>26°C</td>
</tr>
<tr>
<td>16°C</td>
<td>18°C</td>
</tr>
<tr>
<td>11°C</td>
<td>15°C</td>
</tr>
</tbody>
</table>

Table 3.7: Jar tests using PAX at different water temperatures

3.4: Backwashing regimes

The filter was backwashed after every filter run, using water with air scour. The backwash water was supplied from the main building tank and was controlled through a flowmeter with a range of between 6 – 50 litres per minute. The air flowmeter was also capable of reading between 6-50 litres per minute. Backwashing was carried out at a constant rate for the mono-media experiments, so as to provide a control for each run. A theoretical value for the minimum fluidisation velocity, $V_{mf}$, was calculated and is as follows:

$$V_{mf} = \frac{g (\rho_s - \rho) \varepsilon^3 d^2}{180 \mu (1-\varepsilon)}$$

$g = $ Acceleration due to gravity, $\text{m/s}^2$
$d = $ Grain diameter, $\text{m}$
$\rho_s = $ Density of media, $\text{kg/m}^3$
$\rho = $ Density of water, $\text{kg/m}^3$
$\varepsilon = $ Porosity of sand
$\mu = $ Water viscosity, $\text{Nsm}^{-2}$

At 20°C, and using the hydraulic grain size 0.7mm as the value for $d$ (see section 4.2 for hydraulic size calculations), and 0.4 for the porosity;

$$V_{mf} = \frac{9.81 (2650 - 998.23) (0.4)^3 (0.0007)^3}{180 \times 1.0087 \times 10^{-3} (1-0.4)}$$

$V_{mf} = 21.96 \text{ m/hr (7.92 l/min)}$
In practice, the value observed to achieve minimum fluidisation velocity was very similar and was 7.5 l/min. Also observed practically was the rate to achieve 20% bed expansion. This value was 16.5 l/min for sand. This was for clean bed backwashing only, and the values would alter in practice depending on the water temperature and solid loading.

The backwashing regime used for the sand media was a 5 minute water wash at 20% bed expansion followed by 5 minutes of combined water and air scour to produce “collapse-pulsing”, which was 50% of $V_{mf}$ i.e. 4 l/min (11 m/h) water with 23 l/min air (64 m/h). This was followed by a further 5 minutes of water wash.

For the dual media experiments, the regime was altered under the guidance of Paterson Candy Ltd. The column was drained to 0.1 m above the bed, and air scour was then employed for 5 minutes, at 25 l/min (9 m/h). This was followed by 5 minutes of “collapse-pulsing” with 3.6 l/min water and 25 l/min air. Finally 5 minutes of water wash at 20% bed expansion (11 l/min (19.8 m/h) in practice) enabled the regrading of the bed without losing any media.

3.5: Flow rates

The most important variable in this study is the flow rate of water through the column. However it was not just a case of changing the flow at a certain point during the filter run. There were several variables such as the initial flow rate, the percentage flow rate change, the duration of the change and the speed of the flow rate change that required careful planning so as to evaluate all possible combinations of flow.
Prior to any flow change experiments, three runs were conducted of 8 hours and three of 24h duration to establish a control, i.e. to obtain particle breakthrough patterns achieved with a constant flow. This would enable comparisons to be made when a flow change was introduced. This was repeated before each new variable was introduced.

The particle counter used is capable of collecting 250 readings before the data must be downloaded. A sample count can have a minimum duration of 1 second and can be recorded at least every second.

A set procedure for collecting readings was followed for each run. Samples were taken for a duration of 30 seconds as this was the most suitable time period for analysing the data, i.e. it was a long enough time to take a representative reading, yet not too long that the counts would exceed the maximum recordable number. This also eliminated the chance of air bubbles skewing the results, as they would pass through in that time. Counts were taken every 2 minutes for the runs of 8 hours duration as this was the shortest time lapse that would keep within the 250 data limit. The longer runs required a different procedure and so the particle counter was connected to a laptop and data was downloaded in real time into the software package. This enabled much more detailed information to be gathered, as the counting frequency could be brought down to every minute.

3.5.1: Flow changes performed on mono-media bed

Initial experiments were of 8 hours duration and had an initial flow rate of 5m/hr. The influent suspension contained 50mg/l kaolin, so as to simulate the loading effects of a
much longer run, in a much shorter time. The flow was then increased by 25, 50, 75 and 100% for a duration of 30 minutes. The idea was to recreate the flow change that would be observed at a treatment plant when 1 filter in a series was taken offline for backwashing. The change was introduced instantaneously firstly after 1 hour of the filter run, and then after 4 and then 7 hours. To investigate the effects of very late flow rate changes, the runs had to be increased to 24hrs in length. This required the load going onto the bed to be reduced so as to keep the headloss down to realistic levels. These influent concentrations have already been discussed in more detail in section 3.3. Flow increases were applied after 18 and 20h, to illustrate the effects of flow changes on a heavily loaded bed.

To investigate what would happen to the breakthrough patterns if one filter had to be taken offline for repair, the flow increase in the laboratory column was made permanent. 25, 50 and 100% increases were introduced after 1, 4 and 7h using both 10 and 50mg/l kaolin, with only 10mg/l kaolin used for the 22h flow increases. The Badenoch report (1998) suggested that flow changes should only be introduced at a rate of 5% per minute, so as to avoid large particle spikes. This was examined at laboratory scale, with the flow changes being introduced over a period of time. This meant that a 25% flow increase would take 5 minutes to complete at a rate of 45ml/min, whereas a 100% increase would take 20 minutes. As each incremental increases were quite small (as little as 45ml/min), a more detailed scale was placed on the rotameter, which was calibrated beforehand using a measuring cylinder and timer to ensure an accurate flow increase.
The flow changes were temporary, and the flow was decreased instantaneously to the starting flow rate of 1.8l/min. As each flow change was 30 minutes in total, the duration of the maximum flow rate varied between the experiments. For example a 25% flow increase would have 25 minutes of maximum flow whereas a 100% increase would only have 10 minutes, due to the length of time taken to increase the flow. The sketch below (figure 3.3) graphically displays this variation in flow increases.

![Flow rate vs Time graph](image)

Figure 3.3: illustration of varying time spent at higher flow rate, due to gradual increase

3.5.2: Flow changes performed on dual media beds

Once the dual media bed had been created, repeat experiments were performed following the same protocol as many of the mono-media bed experiments. Due to time constraints, only 10mg/l kaolin was used. Temporary, permanent and gradual flow changes were performed after 1, 4 and 20h. However, the only magnitude of flow increase applied on a starting flow rate of 5m/h was 50%. 
The additional benefit of creating a dual media bed was that higher starting flow rates could be investigated. A starting flow rate of 10m/h (3.6l/min) was selected and 25% flow increases were applied after 1, 4 and 20h. The kaolin and alum consumption increased to 4.16ml/min and 1.73ml/min respectively and so the peristaltic pump speeds were increased accordingly. However, it became clear that the column could not support 24h runs at this rate and the flow dropped by approximately 30% during the cycle. This would be an unacceptable drop in productivity at a full-scale plant. Also, the column began to empty during the flow changes, which corrupted the headloss readings. It is possible that the supply valve was not large enough to provide the influent water fast enough. Unfortunately, no time was available to make alterations to the column itself.

For these reasons the starting flow rate was reduced to 7.5m/h. The corresponding dosing rates were 3.18ml/min of kaolin and 1.3ml/min of alum. Again, only 25% increases were performed after 1, 4 and 20h.

3.6: PDA 2000

The Photometric Dispersion Analyser (PDA 2000) was developed by Gregory (1999) to examine the development of flocs after the addition of coagulation, at different stirring rates.
The PDA 2000 works by passing a narrow beam of light, of wavelength 850nm through a clear tube containing the sample. The average transmitted light intensity (dc value), and fluctuating rms (root mean square of the ac signal) value are measured, and the ratio of these two values (rms/dc) gives a measure of particle aggregation, which Gregory has termed the Flocculation Index. The tubing itself has an internal diameter of 3mm and the suspension is passed through the PDA via a peristaltic pump, which is located after the PDA so as not to damage the flocs before being measured. The apparatus can be seen in the schematic diagram below, Figure 3.4.

![Figure 3.4: Schematic diagram of the PDA 2000 apparatus](image)

It was used in this instance to investigate the growth of flocs at different temperatures, and the effect of a sudden increase in stirring rate upon them. This was designed to simulate the increase in shear stress during a flow rate change, and whether the flocs would re-form once the stirring rate was reduced again. Both alum and PAX suspensions were tested, at 3 different temperatures, 10, 18 and 25°C. A 500ml
sample was used, and the particle counter was used in conjunction with the PDA 2000 to get a better idea of the floc size distribution.

The stirring rate was set up to give 10s of rapid stirring (210rpm) to promote the initial mixing. This was followed by 10 minutes of slower stirring (63 rpm), this promoted the floc growth and approximates to the time taken for the suspension to reach the bed. 5 minutes of rapid stirring was then introduced to simulate the increase in shear stress during a flow change. Finally, 10 minutes of slow stirring was conducted to observe any re-formation of the flocs.

The samples through the PDA 2000 were taken every second, with total number of samples 1510. The particle counter sampled for 5 seconds every 15s. Tubes were taped to the sides of the jar to ensure that all samples were taken from the same depth point.

3.7: Video Endoscopy

To investigate the processes occurring within the bed during flow changes, video endoscopy was used to film the floc movement. The process has been developed by Ives and Fitzpatrick (1989) and involves inserting a camera and light source into the media bed via an 8mm rigid borescope. The glass plate at the end of the borescope housing sleeve was etched with a graticule, which was two perpendicular lines 1mm apart. This provided a scale in which to measure the sand grains and the flocs. The lines themselves are 25μm thick. The camera was connected to a high-speed video recorder, which was capable of recording up to 400 frames per second. In this
instance however, a speed of only 200 frames/second was required to provide sufficient detail. A simple diagram of the apparatus can be seen below, Figure 3.5.

![Diagram of the video endoscopy apparatus](Figure 3.5: Schematic diagram of the video endoscopy apparatus.)

The borescope was inserted into the top port of the column, which was located 0.1m below the surface of the bed. Filming was undertaken at the start of each run, and before, during and after the flow change. Each film segment varied in time from 40 seconds to 3 minutes, depending on what was being filmed, i.e. observations at the start of each run required less footage than during the flow change.

The variables investigated included both alum and PAX suspensions, at two temperatures, 16 and 25°C. This enabled the effects of shear on floc at different temperatures to be recorded. 50% temporary flow increases were introduced after 1, 4 and 20h. The video footage is included in the appendix 4 and discussed further in chapter 7.
3.8: Filterflex computer simulation model

In conjunction to the laboratory experiments, work has been carried out on a computer simulation model, Filterflex. This model has been written and developed by Stevenson (1997a) and the theory behind it has been described in more detail in both his work and the previous chapter 2.12. It has many variables which can be altered, including the influent water properties such as viscosity and floc size range, as well as the media properties and flow conditions. For these reasons it was ideal to simulate each type of variable investigated in the column.

A full list of the programmable variables is included in Appendix 3. For each filter run that was performed in the laboratory, a corresponding run was carried out on the model, with the variables being programmed to as close to the filter properties as possible. The results were collated to examine how closely a computer model could predict and simulate the breakthrough patterns in a real filter. These results are discussed in Chapter 8.
4 RESULTS

This chapter details the results obtained in the laboratory. Each variable tested is described individually so that the effects of that particular change can be seen, before more overall patterns and breakthrough behaviour are discussed. Control runs with no flow changes were performed beforehand, so as to examine the background particle counts and run length that could be expected for each different variable.

Unless otherwise stated, the graphs have been grouped to show breakthrough in the 2-5μm range, and also those larger than 5μm. This serves two purposes, firstly it increases the graphical clarity, and secondly it displays particles in the Cryptosporidium range and also those larger flocs which may contain the pathogens. This means that although no actual oocysts have been used in the study, the potential risk of Cryptosporidium passage can be assessed.

4.1: Temporary flow changes

The first variable to be tested was temporary flow change. These were designed to simulate the increase in flow experienced by a filter when another is taken offline for backwashing. They were of 30 minutes duration, and the flow was increased and decreased instantaneously about the starting flow rate of 5 m/h. The flow was increased by a set percentage so the exact numerical flow rate would not always be the same for each experiment, due to the declining rate operation of the filter column. This meant that a 100% flow increase after 1 hour would give a flow rate closer to 10m/h than a 100% increase after 20 hours. Similarly, the flow would be returned to its pre-increase value rather than the starting flow rate of 5m/h. This ensured that all
of the filter cycles underwent identical flow increases and more closely simulated full scale plant operations.

4.1.1: 50 mg/l kaolin influent suspension

The original experiments used a high kaolin concentration of 50mg/l with alum coagulant. This meant that in 8 hours, the solid loading of a far longer filter run could be simulated. The control run (figure 4.11 below) shows that in 8 hours, the particle breakthrough is low and there is no deterioration of the filter efficiency towards the end of the run. All particle sizes are shown in this graph. The flow rate drops by 0.2 l/min, (due to the declining rate operation of the filter) over the 8 hours and the total headloss during that time was on average 0.7m.

![Particle breakthrough during 50mg/l control run](image)

**Figure 4.11: 50mg/l kaolin suspension, 8h control run (5m/h starting flow rate)**

The following graphs show a clear pattern of increased breakthrough during the flow changes. The first graphs, Figure 4.12, show flow increases of varying magnitude
applied after 1 hour. It can be seen that the higher the magnitude of the increase, the more sustained the increased particle breakthrough becomes. During the flow change itself, there is a high initial peak in shedding, which is followed by a gradual secondary increase in breakthrough during the remainder of the flow change. This secondary peak is more obvious in the higher magnitude flow changes. The filter recovers well when the flow returns to normal after the flow changes, and the efficiency of the filter is not reduced towards the end of the run.

Figure 4.13 follows the same format, with flow changes after 7 hours. A more dramatic pattern of increased breakthrough with higher magnitudes changes is evident, as is the failing of the filter after the completion of the flow changes. The secondary peak is also obvious in these graphs. Interestingly, the 50% increase actually causes a higher amount of breakthrough than the 100% flow increase. This is possibly due to a counting error from the particle counter, rather than reduced breakthrough during the 100% flow change. This is because the particle counter was initially set to count for 30 seconds every 2 minutes and so the true peak of breakthrough may have fallen in-between the readings taken. An observation from these graphs is that the higher magnitude increases cause a larger spike of particles in the >5μm range during the first five minutes of the flow change. This is a serious concern as whole flocs are being passed into the effluent, with little recapture.

An interesting point to note is the instantaneous increase in particle shedding once the flow is increased. This is despite a bed resident time at 5m/h is 12 minutes. It suggests that there is potentially a large number of particles at the base of the filter media which is instantly released when the flow is increased.
Figure 4.12: Temporary flow increases of varying magnitudes after 1 h.

- 100% flow increase
- 50% flow increase
- 25% flow increase

Particle counts /ml

Flow /min

Time

Particle counts /ml

Flow /min

Time

Particle counts /ml

Flow /min

Time
Figure 4.13: Temporary flow changes of varying magnitudes applied after 7h, starting flow rate 5m/h (1.8l/min) run duration 9h
The final graph, figure 4.14, shows a 100% increase in flow after 1, 4, and 7 hours. The importance of the timing of the flow change can be seen, as flow changes later in the filter cycle cause more breakthrough than those after only 1 hour. Again, the occurrence of a secondary peak is shown. The failing of the filter subsequent to application of the later flow changes can also be observed (in this graph only the 2-5μm sized breakthrough has been illustrated). The experiments involving a flow change after 7h were left to run for 9 hours in total to observe how the filter recovers and in this case it is apparent that the breakthrough follows the same rate of increase as that after 4 hours, with no recovery at all. Interestingly, not only is the breakthrough low during a flow change after 1 hour, but the base counts for this run are lower too.

![Particle breakthrough with a 100% flow increase at varying times](image)

**Figure 4.14:** 100% temporary flow changes applied at various times during the cycle. Starting flow rate 5m/h (1.8l/min). 1m mono-media bed. 2-5μm sized breakthrough.
Overall, these graphs gave a pattern of breakthrough that was largely to be expected, i.e. the larger the flow increase, the more breakthrough was observed. Similarly, flow changes later in the flow cycle caused larger amounts of shedding. This is because the bed was clogged at deeper depths after 7 hours, so there was less opportunity for the particles to be re-captured. This was compounded by the increased shear caused by the flow change, making attachment less likely. It was observed with the headloss measurements that immediately after the flow change was completed, the headloss was even less than before the increase. This was due to the flow increase removing much of the deposits that had been clogging the media. In the case of the 50% flow increase after 7 hours, the flow change removed the previous 90 minutes worth of floc accumulation.

The secondary peak of particle breakthrough observed in many of the higher magnitude flow changes is likely to be caused by particles being moved deeper into the bed during the initial rise in flow. These were then increasingly shed into the effluent during the remainder of the increased flow period. The peak was instantaneously reduced when the flow was returned to its normal level, which raised the question as to what would happen to this peak if the flow remained high. This was one of the reasons for performing experiments with a permanently increased flow; the results of which are discussed in section 4.2.
4.1.2: 10 mg/l influent suspension

To investigate the effects of flow changes later on in the filter cycle, the concentration of the influent had to be reduced. This was because the headloss build up was too high for the manometer board, which then acted as a bypass for the filter media. The kaolin was reduced to 10 mg/l and flow changes after 18 and 22 hours were applied, in addition to those after 1, 4 and 7 hours.

The control run (not illustrated) shows a similar pattern to that using 50mg/l. There is a slightly longer ripening period of approximately 1 hour, followed by a very stable period where the particle counts are very low. There is no end of run breakthrough, and the total headloss during a 24 hour period is also on average 0.7m. The flow reduction is also identical to the 50mg/l experiments, with a loss of only 0.21/min over the 24 hour period.

The first graph, figure 4.15 shows quite a different pattern of breakthrough from the 50mg/l experiments. There is not an automatic increase in breakthrough with time, and in fact a 22 hour flow change produces less shedding than a 1 hour increase. The particle spikes are of a much shorter duration, and there is no failing of the filter towards the end of the filter run. The secondary peak, which had been evident in the higher concentration experiments, is not as obvious in all bar one of the filter runs using the lower concentration kaolin suspension.
100% flow increases at various times during the filter run. 10mg/l kaolin

Figure 4.15: 100% flow changes at varying times during the filter cycle. (10mg/l kaolin suspension). 1m mono-media bed, starting flow rate 5m/h (1.8l/min) 24h filter runs 2-5μm particle breakthrough.

Figure 4.16 shows how quickly the filter recovers after the flow change, and that for all magnitude increases, an increase after 1 hour has no lasting effect on the filter performance. The higher percentage increases have a higher level of breakthrough during the flow change, and the 100% increase displays a rounded version of a secondary peak.

The final graph, figure 4.17, shows that after 22 hours, a 25% flow increase has absolutely no effect on the filter performance, with no additional breakthrough during or after the flow change. There is again no pattern concerning the magnitude of the flow change with the breakthrough, as a 75% flow increase causes over three times as much breakthrough as a 100% increase.
Figure 4.16: Temporary flow increases after 1 hour. Starting flow rate 5m/h. 8h filter cycles
Figure 4.17: Temporary flow increases after 22 hours. Starting flow rate 5m/h.
It is clear from these graphs that the influent concentration is an important factor in
the overall efficiency of the filter, and although in general the flow changes do cause
some increase in particle breakthrough, it is not as pronounced or as damaging as
when using 50mg/l kaolin. It appears that a certain degree of sediment stability
occurs within the filter between 7 and 18 hours, as the late flow changes rarely cause a
larger amount of breakthrough than those at 7 hours. This is possibly due to
compaction of the sediment, making it less susceptible to the increased shear during
the flow change. Another possibility is the growth of biofilms which could bind the
sediments together. To find out whether there is a certain time threshold after which
breakthrough is reduced would be a valuable area of further research.

4.2: Permanent flow increases

To simulate what happens when a filter in a series is taken offline for repair, the flow
changes applied to the laboratory filter were made permanent. This also enabled
further investigation into the secondary particle peak, which was observed with some
of the temporary flow changes. Flow increases of the same magnitude and at the
same times as the temporary flow changes were applied. Again the increase was
introduced instantaneously, but then left for the remainder of the filter cycle.

4.2.1: 50mg/l kaolin influent suspension

What is immediately apparent with figure 4.21 is that the pattern of increased
breakthrough with time is not necessarily applicable to permanent flow changes (for
these experimental conditions). In fact, it is quite the reverse for most flow changes,
with an increase after 1 hour causing the most 2-5μm sized breakthrough. It can be seen that the flow changes after 4 hours cause an increase in breakthrough towards the end of the filter run, thus shortening the amount of time that the filter performs satisfactorily.

![Particle breakthrough with a 50% permanent increase after 1, 4 and 7 hours. (50mg/l kaolin)](image)

Figure 4.21: 50% permanent increases after 1, 4 and 7h. 5m/h starting flow rate, 1m mono-media bed. 2-5μm particle breakthrough.

This is more obviously displayed in figure 4.22, which shows an increasing amount of end-of-run breakthrough with the higher magnitude flow changes. This is despite showing no distinct pattern of breakthrough during the start of the flow increase. This decreased period of high quality filter performance is to be expected as the prolonged period of increased flow rate means that the solid loading on the filter bed is also increased. The increased shear acting on these deposits causes them to move rapidly through the bed, with less chance of re-attachment.
Figure 4.22: Permanent flow changes of varying magnitudes applied after 4h. 5m/h starting flow rate, 8h filter cycles.
It would appear that a 25% permanent increase does not greatly affect the filter performance, as breakthrough neither increases at the start of the flow increase, nor at the end of the cycle. This was the case for all of the time intervals tested.

Also, with the exception of a 100% flow change, increases after 1 hour do not have any lasting effect on the filter performance, and the breakthrough levels remain satisfactory for the remainder of the filter cycle, once it has recovered from the initial increase in flow (which in all cases was within 20 minutes).

An interesting point to note is that when the flow changes are made permanent, there is no evidence of the secondary peak which was so evident with the high concentration temporary flow changes. This was surprising as it was expected that with a permanently raised flow rate, the secondary peak would be elongated before finding a new equilibrium under the flow conditions. This suggests that there are more factors involved in particle breakthrough than the rate and stability of the flow itself.

4.2.2: 10mg/l kaolin suspension

Again, these experiments were repeated using the reduced kaolin concentration of 10mg/l, and later flow changes were also applied.

These experiments somewhat reinforced the patterns of breakthrough seen with the high concentration temporary flow changes. Figure 4.23 shows flow changes after 4 hours, and it can be seen that higher magnitude increases cause a larger increase in particle breakthrough during the initial period of flow increase. This is the same for all time intervals. There is however, no indication of increased end-of-run breakthrough.
Figure 4.23: Permanent flow changes applied after 4 hours. 10mg/l kaolin suspension. 

Starting flow rate 5m/h. 8h filter cycles
The particle peaks caused by the flow increase after 4 hours itself was very short lived, and the filter quickly recovers, even with a doubling of the flow. This is more evidence to confirm the importance of the influent concentration, and the fact that each filter has its own solid loading capacity, above which the effluent quality will decrease.

Figure 4.24 shows that although magnitude patterns have been restored, the idea of increased breakthrough with time is not necessarily true for all conditions. These graphs show that a 100% flow change after 1 hour causes more shedding than any other flow increase, except for that after 20 hours. It has been found that when the flow is increased after 1 hour, the filter has not finished ripening, as the particle counts are still raised. This can be seen in this graph, and was evident in all of the experiments.

![100% permanent flow increases at varying times](image)

Figure 4.24: 100% permanent flow increases at varying times during the cycle.

10mg/l kaolin suspension, 8 or 24h filter cycles. Starting flow rate 5m/h
This may account for the increases after 1 hour causing more breakthrough than at more stable times in the filter cycle, for example 4 and 7 hours. This 1 hour flow increase also displays a suggestion of a secondary peak, and certainly a period of increased breakthrough straight after the flow increase, rather than the short lived initial spike observed for other conditions. This extended breakthrough was evident with the 1 hour flow increases, which was due to the lack of ripening already mentioned, and also the 20h flow increases, which was almost certainly due to the amount of sediment retained in the bed by this time.

Overall, other than the spike during the initial flow increase, the filter performs well for all of the variables tested and despite the increased rate of flow, the particle counts remain at low levels with no indication of a reduction of run time.

Figure 4.25 displays the total number of particles passing through the filter during the first hour of the flow increase, and also during the entire run. 50% flow increases are displayed after 1, 4 and 7h for both influent concentrations.

Figure 4.25: Comparison of total particle shedding between kaolin concentrations
The graph illustrates that for both influent concentrations, particle breakthrough is worse when the flow is increased after 1 hour, and that a large proportion of this comes from the shedding during the first hour of the flow increase. It also shows that in both cases an increase after 4 hours is least damaging to the overall performance of the filter, probably because the filter has reached stable operation, but has not yet accumulated enough sediment within the bed to cause massive breakthrough when the flow is increased.

However, the most interesting point to this graph is the actual particle breakthrough numbers between the two influent concentrations. Despite the 50mg/l suspensions being 5 times as concentrated, the actual levels of breakthrough are very similar to that of the 10mg/l influent. This is very surprising, given the levels of shedding observed with the 50mg/l kaolin temporary flow change experiments. On further investigation, it was found that the only variable to differ between the experiments was the water temperature. All of the high concentration experiments had been carried out during the winter, when the influent water temperatures were up to 10°C lower than those used in the 10mg/l kaolin experiments. This was the first suggestion that the influent temperature plays an important role in the overall filter efficiency, and work was carried out to investigate these effects in more detail. This work is discussed in chapter 5.1.

4.3: Gradual flow changes

Having seen the effects of instantaneous flow changes on the filter, it was decided to investigate the recommendations made in the Badenoch (1995) and UKWIR (1999) reports, that any flow changes introduced to a filter should be carried out at a rate no
greater than 5% per minute. Temporary flow increases were applied at similar magnitudes and times to the previous variables. The total flow changes were of 30 minutes duration, and the percentage increase determined the amount of time spent at the higher flow rate, as previously described in chapter 3.5.

4.3.1: 50mg/l influent suspension

Only 50% flow increases were applied to the filter using the higher concentration, due to time constraints.

Figure 4.31 shows a 50% gradual flow increase after 1, 4 and 7h. It can be seen that despite the fact that the filter had not finished ripening, a flow increase after 1 hour has no effect on the filter, either during the flow change, or a subsequent reduction in efficient run time. The 4 and 7 hour flow changes cause a very similar amount of breakthrough, with peaks of approximately 120 counts/ml.

![50% Gradual flow increases at varying times during filter cycle](image)

Figure 4.31: 50% gradual flow changes applied at varying times during the cycle. 50mg/l kaolin suspension, starting flow rate 5m/h. 8h filter cycles 2-5μ
It would appear that a gradual increase compensates for the additional three hours of solid loading, and both recover quickly once the flow was returned to its lower value. None of the runs tested suffer end-of-run breakthrough. Although the 4 and 7 hour increases show increased levels of breakthrough for the entire duration of the flow change, the peak values themselves are far less than the corresponding high concentration temporary flow changes, which suggests that the gradual introduction of the flow change greatly benefits the filter in terms of reduced shedding and overall efficiency.

4.3.2: 10mg/l influent suspension

Far more variables were tested using 10mg/l kaolin. Figure 4.32 shows breakthrough during a 50% flow increase after 1, 4, 7 and 20 hours. It is obvious again that the most damaging flow changes occurs after 7 hours, with a maximum breakthrough peak of 620 counts /ml. This pattern corresponds well with the 10mg/l temporary increase experiments, and likewise sediment compaction or biofilm growth may be attributed to the reduced breakthrough after 20 hours. Outside of the flow changes the filter performs very well, with no deterioration towards the end of the filter cycle. The breakthrough levels remain raised during the actual flow changes but quickly reduce to background levels once the flow change is completed.
50% gradual flow increases at varying times during the filter cycle (10mg/l kaolin suspension, 5m/h starting flow rate.) 8 and 24 filter cycles.

Figure 4.33 shows different magnitude flow changes after 4 hours. Again there seems to be no pattern of increased breakthrough with the higher flow changes. A 25% flow increase results in the most breakthrough, whereas a 50% change shows no increase in breakthrough at all. The 25% increase also has a short lived secondary peak during the flow change. Interestingly the 50% experiment which resulted in very little breakthrough had the coldest influent water temperature (15°C) of all the 10mg/l runs.

There is no failing of the filters for any magnitude flow increase, and all runs have satisfactory performance for the whole duration (with the exception of during the flow changes). Unlike the 50mg/l experiments there seems to be no overall reduction in breakthrough between the gradual flow changes and the instantaneously introduced temporary changes. One reason for this could be the water temperature.

Figure 4.32: 50% gradual increases at varying times during the cycle (10mg/l kaolin suspension, 5m/h starting flow rate.) 8 and 24 filter cycles.
Figure 4.33: Gradual flow changes of different magnitudes applied after 4h. 10mg/l kaolin suspension. Starting flow rate 5m/h.
Whereas the temporary flow changes were both carried out at similar water temperatures, the 50mg/l gradual increase experiments were performed in winter and thus had colder temperatures than the 10mg/l gradual experiments. This could also explain the similar, and in some cases reduced, amount of breakthrough with the higher concentration runs, despite the higher influent turbidity. This relates very well with the patterns observed between the two concentrations of permanent flow increase experiments. It could be that alum does not perform as well at higher temperatures (despite several published reports to the contrary, for example Hanson and Cleasby, 1990) and so is more susceptible to breakthrough during periods of flow change. This will be discussed in more detail in chapter 5.1.

In general, although introducing flow changes gradually can cause a reduction in the amount of breakthrough caused by the increase in flow, it is becoming clear that it is the temperature of the influent that determines the effectiveness of the additional measures to control the particle breakthrough.

4.4: Reduced bed depth

Not all treatment plants use an identical filter bed depth when designing the filters. To investigate how the depth of the media affects the overall performance of the filter, the media in the laboratory column was removed to leave a bed depth of 0.6m of 0.5-1mm sand. For these experiments the only influent suspension used was 10mg/L kaolin.
Temporary, permanent and gradual increases were performed at 25% and 50% after 1, 4 and 20 hours. The control runs (Figure 4.41) produced a pattern of very good performance for approximately 19-20 hours but then suffered quite substantial end of run breakthrough, rising to more than 1000 counts /ml in the 2-5μm range by the end of the 24h cycle. This was largely expected given that there was less media to retain the flocs. The total headloss over the 24h period reached on average 0.8m.

![Reduced bed control run](image)

Figure 4.41: 0.6m bed depth control run. 0.5-1mm sand, starting flow rate 5m/h. 24h filter cycles, 10mg/l kaolin suspension

4.1.1: Temporary flow changes

Figure 4.42 illustrates the effects of flow changes of differing magnitudes after 20 hours. Both graphs display limited particle breakthrough for the main duration of the cycle. A 25% flow increase causes only a minimal increase in particle counts, and good filtration is quickly restored for the remainder of the run.
A 50% increase causes a higher amount of breakthrough which remains at a higher level for the entire duration of the flow change. This mirrors the results observed with a deeper (1m) bed in summer conditions. However, immediately after the flow change, the filter begins to fail, and particle breakthrough rapidly increases.
Figure 4.42: 25 and 50% temporary increases after 20h. 5m/h starting flow rate, 10mg/l kaolin suspension, 24h filter cycles.

It would appear that perhaps a 25% flow increase is not sufficient in magnitude to cause a lasting disturbance to the bed, despite having 20 hours of solids accumulation on the reduced media.
Figure 4.43 shows that the pattern of increased breakthrough with time is also evident when using a reduced depth of media. The graph displays 50% flow increases after 1, 4 and 20h (7h increases were not investigated due to time constraints). It can be seen that for the main duration of the filter cycles, the particle counts are very low and the filtration is good. With a flow change after 1 hour, there is virtually no disturbance during any part of the run, and there is no early end of run breakthrough. With a 4h flow increase there is a definite particle spike during the flow change itself, but this is short lived, and the end-of-run breakthrough only reaches 50 counts /ml. The 20h flow increase shows a much higher level of breakthrough during the entire flow change, and subsequent filter failing for the remainder of the run. However, the much longer ripening period of this filter run hints that additional factors may have influenced the experiment, for example the coagulation process if not optimised.

Figure 4.43: 50% flow increases after 1, 4 and 20 hours. Reduced media depth, 10mg/l kaolin suspension. 5m/h starting flow rate (1.8l/min)
4.4.2: Permanent flow changes

When the flow changes were made permanent, an identical breakthrough pattern of increased breakthrough with time can be seen. Figure 4.44 shows a 50% flow increase after 1, 4 and 20h. It can be seen that as with the temporary flow changes, a 1h increase causes very little disturbance to the bed. The 4 hour flow change, despite not causing any additional breakthrough when the flow is increased, begins to fail earlier than the temporary increase experiment. This is expected due to the longer period of higher solid loading. Finally, the 20 hour flow increase does show a large particle spike when the flow is first increased, and also an immediate failing of the filter after the initial shedding. The rate of breakthrough closely matches that of the 4 hour increase experiments, suggesting that once the filter has been saturated, similar shear conditions will result in the same amount of shedding.

![Image: 50% permanent flow increases after 1, 4 & 20h]

Figure 4.44: 50% permanent flow increases at different times during the cycle. 10mg/l kaolin suspension, 5m/h starting flow rate 2-5μm breakthrough.
4.1.3: Gradual flow changes

The final variable investigated using the 0.6m filter bed was a gradual flow increase. These followed the same protocol as that used on the 1m deep bed.

Figure 4.45 shows 25 and 50% flow increases after 20h. It can be seen that as with all of the variables tested, the particle counts during the main body of the run are very low, and the filter performs well. However, when a 25% gradual flow change is introduced, there is a significant increase in particle breakthrough which remains above base levels for the duration of the increase. Also there is immediate failing of the filter following the flow change. This breakthrough is far higher than that observed with the temporary flow increase, despite the flow change being introduced slowly. When a 50% increase is performed, the breakthrough spike is even more pronounced, which is expected, firstly due to the higher magnitude of flow increase, and secondly because the filter was already beginning to fail, suggesting that the bed was saturated. In this instance, the breakthrough is higher in the >5\(\mu\)m size range, suggesting that entire flocs were being detached. The slightly anomalous pattern of breakthrough after the flow change is thought to be due to the unstable flow rate after the increase but the failure of the filter is clear.

Figure 4.46, illustrates 50% flow increases after 1, 4 and 20h. It can be seen that only an increase after 20 hours causes any breakthrough during the actual flow change itself. However, all three runs suffer end of run breakthrough, including the 1 hour flow change, which had not been observed with any of the previous variables (i.e. temporary and permanent flow increases performed on the 0.6m bed). The 4 hour
flow change experiment experiences the shortest duration of satisfactory filtration, with breakthrough occurring after only 14h.

![25% Gradual flow increase +20h](image)

**Figure 4.45**: 25 and 50% gradual flow increases after 20h. 0.6m bed depth, 10mg/l kaolin suspension, 5m/h starting flow rate.
As with the permanent flow increases, the rate of shedding at the end of the runs are very similar (allowing for the disturbed breakthrough during the 20h experiment, previously mentioned).

Overall, these results have shown that reducing the media bed will, as expected, cause the duration of satisfactory filtration to be reduced. All runs suffer large particle spikes when flow changes after 20h are introduced, and with the exception of the temporary 4h flow change, these are the only increases that cause additional breakthrough. Gradual flow increases do not appear to cause a significant reduction in breakthrough compared to the instantaneously induced temporary increases, especially when considering the end of run breakthrough. This is surprising, given the largely successful introduction of gradual flow changes on the 1m media bed. The patterns of increased breakthrough with both the time and magnitude of the flow change can clearly be seen, and these correspond well with the initial 50mg/l kaolin experiment on the 1m media bed. Interestingly, all of the reduced bed experiments
were conducted in summer influent conditions, which have repeatedly shown these patterns of increased breakthrough.

4.5: Dual media bed experiments

To recreate the filter conditions observed at the full-scale plants in Wales (see chapter 6), the media configuration was changed to include anthracite. The bed profile for the column was 0.5m sand (0.5-1.0mm) and 0.3m of anthracite (1.18-2.36mm). Using a kaolin concentration of 10mg/l, temporary, permanent and gradual flow changes were applied after 1, 4 and 20 hours. 50% increases were the only variable tested. Control runs (not illustrated) gave a ripening period of approximately 40 minutes followed by excellent filtration, particle counts were very low and there was no end of run deterioration. The maximum headloss over 24 hours was approximately 0.75m, and in this time the flow rate dropped by 0.15 l/min, which compares to headloss build up of 0.7m and flow reduction of 0.2l/min for mono-media sand.

4.5.1: Temporary flow changes

Figure 4.51 shows particle breakthrough during temporary flow changes after 1, 4 and 20h. Firstly, it is obvious that in general the filter performs very well, as particle counts outside of the flow changes are very low (which was similarly observed during the 10mg/l kaolin suspension experiments using sand only). The pattern of increased breakthrough with the later flow increase is observed in these experiments. The breakthrough peaks during the flow changes are mostly short lived and the particle counts quickly revert to stable operation levels.
Figure 4.51: 50% temporary flow increases after 1, 4 and 20h, dual media bed, starting flow rate 5m/h. 10mg/l kaolin suspension.
With the flow change after 20 hours however, some failing of the filter is observed before the flow change and the breakthrough peak is very high once the flow is increased. This is the only experiment that displays an increase in shedding for the entire duration of the flow change, and for some time thereafter. However, once the additional breakthrough has reduced, the filter performs well, and does not continue to fail. The headloss values for these filter cycles are less than those recorded with the 1m sand media, as was expected with the coarser media. This leads to the speculation that if flow changes are restricted to the early period of a filter run, the actual run length could be greatly increased with no detrimental effect to the filter performance. Also, over the 24 hour period, the flow rate does not drop as much as when using only sand, in most cases the flow was reduced by only 0.15l/min on average. This makes the filter more efficient as more water can be treated in the same time period. (However, this only applies to declining rate filtration, which is not as common as steady rate filtration)

4.5.2: Permanent flow changes

Figure 4.52 shows very similar graphs, but with flow changes being applied permanently. Unfortunately, due to a mechanical fault, flow rates have not been recorded for these experiments. Again, stable operation particle counts are very low, but during the flow increase the breakthrough pattern is different in that the 1 hour increase causes the highest particle spike, and the longest amount of subsequent disturbance before the filter operation recovers and performs well. The 4 hour increase causes the least additional breakthrough, Interestingly this was identical to the pattern observed with the mono-media experiments.
Figure 4.52: 50% permanent increases after 1.4 and 20h, dual media bed, 5m/h starting flow rate. 24h filter cycles.
None of the experiments produced early end-of-run breakthrough. A concern with the introduction of the permanent flow changes is the high proportion of breakthrough in the >5μm size range. This suggests the increase in shear stress is removing entire flocs straight away. This breakthrough is very short-lived however, and the filter has a good recovery rate.

Overall, the filter copes very well with the increased flow and the results suggest that the filter would be able to handle higher starting flow rates. This was investigated and is discussed in section 4.6.

4.5.3: Gradual flow changes

These final graphs, figure 4.53 show 50% gradual flow changes. They show that the filter performs excellently during stable operation and also during the flow changes in terms of particle counts. A 1 hour flow increase causes no additional breakthrough, and even after 20h the shedding peaks at only 48 counts /ml. This, similarly to the permanent flow increase, was in the >5μm size range. There was no visible end-of-run breakthrough, and the headloss build up was the lowest of all of the variables tested using dual media. These graphs show that gradual flow changes applied on a dual media cause the least damage to filter operation in terms of particle breakthrough. This is likely to be due to the larger pores in the anthracite, which result in a lower increase in shear when the flow rate is increased.
Figure 4.53: 50% gradual flow increases after 1.4 and 20h. Dual media bed, 5m/h starting flow rate, 24h filter cycles.
Overall, the dual media filter performs far better than the mono-media experiments, in terms of both particle breakthrough and run time capacity. None of the filter runs displayed any deterioration at the end of the cycles which suggest that the runs could be extended. This was the case for all of the flow variables, even the permanent flow increases, despite the increased solid loading. The gradually applied flow increases cause the least breakthrough of all the variables tested. All of the dual media experiments were performed in winter with cold influent water. This may have helped to keep the breakthrough to a minimum, as seen with the mono-media experiments.

4.6: Higher starting flow rates

Having observed the filtration efficiency using dual media for 5m/h, even during permanent increases, investigations were made into the performance of the filter under higher starting flow rates. Start rates of 10 and 7.5m/h were used, and temporary flow changes were applied after 1, 4 and 20h. Given the high starting rate, only 25% increases were applied.

4.6.1: 10m/h starting rate

Control runs were performed (as shown in figure 4.61) and it was found that effective filtration could only be maintained for approximately 9 hours, after which the particle shedding rapidly increased to above 5000 counts /ml.
When temporary flow changes were applied, the same pattern emerged, as seen in figure 4.62. The filter is only effective for approximately 14 hours, although during this time, the actual flow changes themselves made little impact on the amount of particle breakthrough after 1 and 4 hours. An exception to this is the 20 hour flow change, which suffered a large amount of shedding, especially in the >5\(\mu\)m range, during the flow change as the filter had already started to fail. After the flow is reduced the shedding drops rapidly and then increases at a much faster rate than before the flow change, before gradually slowing to the same rate as the earlier end-of-run breakthrough. The flow rate dropped by a total of 0.9 l/min, which is 25% of the total flow. Also, the apparatus could not support the very high flow rates and during the flow changes the column began to empty. This meant that the headloss values were not accurate. For this reason, the start flow rate was reduced to 7.5 m/h, and the experiments were repeated.
Figure 4.62: 25% temporary flow increases applies after 1.4 and 20h. 10m/h starting flow rate (3.6l/min) 10mg/l kaolin suspension. 24h filter cycles.
4.6.2: 7.5m/h starting rate

The control runs performed at this starting flow rate produced a similar pattern of breakthrough as for 10m/h. Good filtration can only be maintained for approximately 11 hours, and in 24 hours the flow dropped by 0.7l/min.

Figure 4.63 shows that, as with the previous experiments, 25% temporary flow changes were applied after 1, 4 and 20h. The graphs show that the filter performs satisfactorily for 10-14 hours (although there is suspect performance of the filter for the first 4 hours of the first experiment when applying a 1 hour flow increase. This may have been due to a blockage within the particle counter). With flow changes after 1 and 4 hours, the actual increase has no significant detrimental impact on the filter performance, with no additional particle breakthrough. End of run breakthrough is obvious however, and reaches similar breakthrough levels to those seen during the 10m/h experiments, i.e. approximately 2500 counts /ml. With an increase after 20 hours, a different pattern is observed. As the filter had already begun to fail, with deposits distributed throughout the bed, the flow increase causes a large particle spike, particularly in the >5μm range. This substantial initial increase appears to have flushed through many of the particles held within the bed. For the remainder of the flow increase (approximately 20 minutes), the breakthrough levels are comparatively much lower. However, once the flow has been returned to its pre-increase levels, the particle breakthrough levels rapidly increase and continue at a rate similar to that before the flow increase. It would appear that despite removing much of the deposits clogging the bed, such a shock to the filter reduces its capacity for subsequent particle removal.
Figure 4.63: 25% temporary flow increases after 1.4, and 20h. 7.5m/h starting rate.

Dual media bed, 10mg/l kaolinite suspension
Again with these experiments, the column could not maintain the additional flow during the temporary increase. However, this was limited to the 4 and 20 hour flow changes. Unfortunately, time constraints prevented alterations to be made to the column which may have rectified this problem.

Overall, it would appear that for these experimental conditions and apparatus, higher starting flow rates, both 7.5 and 10m/h are not suitable for efficient filter runs. Although the filter performs well for the first 12 hours or so of the run, this performance cannot be maintained and the end-of-run breakthrough is rapid and significant. This is despite earlier suggestions to the contrary from the dual media experiments (section 4.5), which indicated that filtration duration could be substantially extended. It maybe that with some alterations to the column apparatus, more efficient runs could be performed without the problems of the column emptying. This in itself may have affected the floc formation as it resulted in a more turbulent influent water, due to the drop between the inlet pipe and the water level in the column. This may be another factor in the deterioration of the filter performance.

4.7: Polvaluminium chloride (PAX) coagulant

All of the previous experiments have been conducted using alum as the chemical coagulant. As many of the experiments produced results that suggested that the overall performance of the filter was dependent on the influent water temperature, an alternative coagulant was tested to observe its performance under a range of temperatures. PAX was chosen as it has been reported to provide similar filtration
results regardless of the temperature (Exall and Vanloon, 2000). For these experiments the bed consisted of 1m of mono-media sand, so as to provide a direct comparison to the experiments using alum. 25 and 50% temporary flow changes were applied after 1, 4 and 20 hours at two influent water temperatures, 16 and 25°C. The temperature was controlled thermostatically in the supply tank, and may have varied by 1-2°C by the time the suspension reached the filter. 10 mg/l kaolin was used as the influent suspension.

4.7.1: Influent water temperature 16°C

The control runs, (not illustrated) show a pattern of mediocre filter performance, with breakthrough base levels in the range of 50-100 counts/ml for the entire run. Throughout the 24 hour runs, the flow dropped a total of 0.4l/min, which is slightly higher than when using alum, and the headloss rose to approximately 1.3m. This is also higher than the alum experiments, which recorded values of 0.2l/min flow reduction and 0.7m headloss.

Figure 4.71 shows 25% temporary flow increases after 1,4 and 20h. It can be seen that for the majority of the filter run duration, the filter performs consistently, with fairly low particle counts. The exception to this is the experiments using a 20 hour flow change. This has base counts of approximately 100/ml in the 2-5μm range. This would be an unacceptably high level of breakthrough if encountered at a full-scale plant. The variation between the base counts raises the question as to the optimisation of the coagulant, as no other research has found this poor performance with PAX.
It can also be seen that the flow increases have very little impact on the filter with no spikes occurring after 1 or 4 hours, and only limited additional shedding after 20 hours. However, despite this stable early performance, all of the runs suffer end of run breakthrough, with effective filtration only being maintained for approximately 19 hours (with the exception of the 1h experiment which failed earlier). This was another effect that was not observed when using alum.

![25% temporary flow increase after 1, 4 and 20h](image)

Figure 4.71: 25% temporary flow increases after 1, 4 and 20h (16°C) 1m sand bed, starting flow rate 5m/h (1.8l/min) 24h filter cycles

Figure 4.72 shows 50% increases after the same time intervals. They are displayed separately so as to better show the individual effects. It can be seen that, similarly to one of the 25% experiments, the base counts are actually quite high in the 2-5μm range. This suggests that PAX does not have superior performance over alum at colder temperatures. The pattern of increased breakthrough with time is evident in these experiments, with an increase after 1 hour having no effect, but after 20 hours the breakthrough is quite substantial. Again, breakthrough occurs towards the end of
the filter cycle, and similarly to the 25% experiments, this is after about 18h. The 20h increase experiment is slightly different in that the filter performance was good until the flow change, after which the filter fails rapidly. This delay may be due to the interruption in flow at the start of the run which resulted in a second ripening peak, thus delaying the stable period of filtration.
Figure 4.72: 50% temporary flow increases after 1, 4 and 20h (16°C). 1m mono-media sand bed, 5m/h starting flow rate, 10mg/l kaolin suspension, 24h filter cycles.
Overall, these results suggest that the use of PAX at reduced laboratory temperatures is not as effective as when using alum, due to the shorter run times and more rapid loss of flow. Headloss build-up is also much greater, which is often an automatic parameter for backwashing at full scale plants.

4.7.2: Influent water temperature 25°C

This set of experiments were performed to establish whether PAX performed better than alum at higher temperatures, which in the laboratory had already been shown to perform less well in the summer, than in the winter.

Figure 4.73 shows the 25°C control run. It can be seen that, as with several of the cold PAX experiments, the base counts are quite high (approximately 60-100 counts/ml), and there is a gradual increase in particle counts over the latter half of the run.

Figure 4.73: PAX Control run with influent temperature 25°C. Starting flow rate 5m/h, 10mg/l kaolin suspension. 1m mono-media sand bed.
This is only true of the 2-5μm size range, as the breakthrough in the larger size range remains very low throughout the entire run. This may be that PAX in general forms much smaller flocs and so contains fewer flocs >5μm anyway, or that the filter is more efficient at retaining the larger particles. The flow also drops more over 24 hours at higher temperatures, with a loss of 0.5l/min.

Figure 4.74 shows 25% flow increases after 1, 4 and 20h. It can be seen that all of the runs have a high particle base count, but unlike the cold PAX runs, only the 1 hour experiment suffers any early end-of-run breakthrough. None of the experiments display any additional shedding during the actual flow changes, suggesting that 25% is at the lower end of the scale for causing disruption to the filter. This performance is almost identical to the experiments using a water temperature of 16°C.

![25% temporary flow increases after 1, 4 and 20h. (PAX at 25°C)](image)

Figure 4.74: 25% temporary flow increases after 1, 4 and 20h (25°C) 5m/h starting flow rate
However, when the magnitude of the flow change is increased to 50%, as shown in figure 4.75, the familiar pattern re-emerges. Firstly it can be seen that the later the flow change is applied, the larger the breakthrough spike becomes. With the 20h flow change, the breakthrough levels remain raised for the entire duration of the flow change. Again, early end-of-run breakthrough is observed for all filter runs, although the shedding reaches far higher levels with flow changes after 1 and 4 hours, reaching 1500 counts /ml in the 2-5μm range. There are some random spikes occurring towards the end of these filter cycles, but these are thought to be disturbances to the apparatus during working hours. Base rate counts are similar to the previous 25% increase experiments, with 2-5μm counts averaging at about 70-100 /ml.
Figure 4.75: 50% temporary flow increases after 1.4 and 20h (25°C) PAX coagulant, 10mg/l kaolin suspension. Starting flow rate 5m/h. 24h filter cycles.
Overall, experiments using PAX have yielded very similar results, regardless of the temperature. It can be seen that the higher magnitude flow increases cause more breakthrough, both in terms of the immediate shedding and also with the end-of-run breakthrough. It would appear that a 25% flow increase is close to the threshold for causing disturbance to the filter, as very few of the runs experienced any additional breakthrough. These trends correlate very well with the temporary alum experiments. However, the base particle counts when using PAX for all conditions is far higher than when using alum. Unlike the original experiments the use of PAX shortens the time for effective filtration to approximately 18h. This would make it less economical to use at treatment plants, despite the reduction in actual chemical dosing required for effective flocculation, compared to alum.

Temperature itself seems to play very little part in affecting the filter performance, with similar particle counts being recorded between the experiments. The exception to this is the early failing of the cold 25% PAX runs. The similarity in breakthrough is

Figure 4.76: Headloss comparison between PAX experiments at different temperatures. 24h filter cycles, 5m/h starting rate.
despite the difference in water viscosity at different temperatures. This is shown by the varying headloss development rates illustrated in figure 4.76. The maximum headloss is far higher than the corresponding alum experiments. This concurs with previous literature that PAX performance is largely independent of temperature (Exall and Vanloon, 2000). Further investigation of the comparison between PAX and alum floc development at different temperatures is detailed in the following chapter.

4.8: Summary of Results

This chapter has detailed the results of the experiments conducted in the laboratory. What has been found is that without a doubt, flow changes do cause an increase in particle breakthrough, and that in general, the timing and magnitude of the increase can determine the amount of shedding observed. There are some obvious exceptions to this, and it would appear that external variables can be equally, if not more important in determining how damaging a flow change will be. One of the most influential variables was the water temperature, and this is discussed in chapter 5.

It can be seen that in most cases, a 25% flow increase is least damaging to the filter in terms of breakthrough and filter recovery, with many experiments observing no additional breakthrough during these flow changes. Whereas this is encouraging for WTW operation, it must not be forgotten that there are cases where this magnitude of increase does cause a high amount of breakthrough, and the overall condition and filter processes must be taken into account when trying to predict breakthrough.
The dual media bed experiments have proved to be largely successful in reducing the amount of particle breakthrough, in particular the introduction of gradual flow changes proved to be an excellent means of limiting breakthrough for these conditions. However, this good performance cannot be extended to the experiments using higher flow rates. Although the filter showed very limited breakthrough during the early part of the runs, this could not be maintained for very long, and massive end-of-run breakthrough was observed. Run times may have been extended by altering the filter design itself, but was not practical during this study.

The following chapters go further to explain the reasons behind some of the breakthrough unrelated to flow changes, and why some of the variables tested did not conform to the predicted patterns of breakthrough. Comparisons to the full-scale plant operation and results are also detailed, which provide valuable confirmation of some of the breakthrough patterns observed in the laboratory.
5 EXTERNAL VARIABLES AFFECTING FILTER PERFORMANCE

In compiling and analysing the results of the original flow variables, it became clear that there were several factors that influenced the breakthrough characteristics of the filter, other than just the magnitude and timing of the flow change itself. The external variables investigated were;

- The influent water temperature,
- The subsequent shear stress variations,
- Vibrations affecting both the laboratory apparatus and one of the full-scale treatment plant locations.

All of these factors are detailed individually in this chapter.

5.1: Influent water temperature

The variation in water temperature between summer and winter conditions in the laboratory ranged between 14°C and a maximum of 26°C. This appeared to have quite a significant impact on the amount of breakthrough, so repeat experiments were performed where the only variable was the water temperature, to analyse this difference in particle shedding.

Figure 5.11 below is a very good illustration of the trend that was found with all of the variables tested. The graph shows two 8h runs using 50 mg/L kaolin. 100% temporary flow changes were applied after 4h, and the two water temperatures were 16°C and 22°C. It can clearly be seen that prior to the flow change, both runs had a
fairly similar ripening period (although the colder 2-5μm size range took the longest
to ripen), and subsequent good filter performance.

![Comparison of particle breakthrough at different water temperatures. 100% flow increase +4h (50mg/l kaolin)](image)

**Figure 5.11:** Particle breakthrough observed at different influent water temperatures, using a 1m mono-media bed and a starting flow rate of 5m/h (1.8l/min = 5m/h)

However, during the flow change itself, the run at 22°C suffered significantly higher
levels of breakthrough, both in the 2-5μm range, and even more so in the >5μm range,
which suggested that entire flocs were being detached. A secondary peak is clearly
visible, which drops off the instant that the flow is reduced. However immediately
afterwards, the filter begins to fail at an increasing rate. By the end of the filter cycle,
the breakthrough in the 2-5μm range is approximately 2000 counts /ml.

In contrast the run performed at 16°C shows very little breakthrough during the flow
change, and although the particle counts remain above base counts for the entire
duration of the flow change, once the flow is reduced, the filter quickly recovers and
the shedding remains low for the remainder of the filter cycle, with no indication of any end-of-run breakthrough.

This was quite the reverse of what was expected to happen, given the higher shear stress and reported poor performance of alum at low temperatures. It would be expected that much higher particle counts would be observed during the 16°C run. The superior performance of the filter at cold temperatures was observed in all experiments.

5.1.1: Jar Tests at varying temperatures

In order to investigate the reasons behind the variations in filter performance at different temperatures, jar tests were performed to visualise the floc development and subsequent turbidity readings.

As previously mentioned in Chapter 3.32, The suspension that was tested was 800ml of London tap water, dosed with 50mg/l kaolin and 0.19ml/l Alum (M/10). This had been established previously as the optimum dosing level. The temperatures tested were 25, 16 and 11°C. The jar test rig was set to perform 15 seconds of rapid mixing followed by 10mins of slow stirring. 15 minutes settling time was set before the final turbidity reading was taken. Turbidity samples were taken from the 600ml mark on the jars. The initial turbidity of the kaolin suspension was on average 58NTU.

The results and visualisations are displayed in table 5.1.
These jar tests show that larger flocs form in warmer water, and have a faster settling time. The laboratory experiments have shown that more detachment occurs in warmer water, despite the lower viscosity and consequent reduced shear force with increased water temperature.

The flocs do not appear to be more dense in colder temperatures, as there is no settling during the last 15 minute settling phase (although this could possibly be due to their small size). Despite this, the results suggest that small flocs created using alum at cold temperatures are not weak, as they can withstand higher shear stresses caused by the lower viscosity of the water.

5.1.2: PAX and alum comparisons

Having established that the performance of alum flocs is greatly influenced by temperature, and thus possibly not suited to plants which experience a wide range of water temperatures, the results were compared to the performance of PAX. Firstly,
the jar tests at different temperatures were performed, using the same protocol as the alum jar tests. To provide a better comparison, 50mg/l kaolin was used, despite only 10mg/l kaolin being used in the filter experiments. Table 5.2 below details the floc formation and turbidity readings during the jar tests.

<table>
<thead>
<tr>
<th></th>
<th>25°C</th>
<th>16°C</th>
<th>11°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INITIAL VISUAL OBSERVATIONS</strong></td>
<td>Rapid flocculation, large flocs after 2 mins</td>
<td>Similar floc development between temperatures, much slower than 25°C, only small flocs after 3 mins</td>
<td></td>
</tr>
<tr>
<td><strong>10 MINUTE TURBIDITY</strong></td>
<td>5.4</td>
<td>12.8</td>
<td>12.9</td>
</tr>
<tr>
<td><strong>10 MINUTE OBSERVATIONS</strong></td>
<td>Large flocs show rapid settling</td>
<td>identical looking floc size. very slow settling</td>
<td></td>
</tr>
<tr>
<td><strong>15 MINUTE TURBIDITY</strong></td>
<td>2.2</td>
<td>7.5</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>FINAL TEMPERATURE</strong></td>
<td>26°C</td>
<td>18°C</td>
<td>15°C</td>
</tr>
</tbody>
</table>

Table 5.2: Jar tests using PAX at different water temperatures

The results of these jar tests have shown that at lower temperatures, the floc development is very similar and appears not to be dependent on the actual water temperature. However, the highest temperature tested showed far superior development, with rapid flocculation commencing within 2 minutes. The floc development at this temperature was almost identical to the corresponding alum flocs. Once the mixing period had been completed (i.e. after 10 minutes), the residual turbidity was lower when using PAX, and this was the case for all water temperatures. However, it would appear that the PAX flocs could be less dense than alum flocs as the turbidities after the settling period were all higher, and the visual observations during this period confirmed that the flocs do not settle as well.
Having established the speed and degree of floc development at different temperatures, laboratory filter runs were repeated to compare the performance of the two coagulants.

25% and 50% temporary flow changes were applied after 4 hours using 10mg/l kaolin. The water temperatures during these experiments were 14 and 24°C. The 2 graphs are displayed as block diagrams of the total particle counts in the 2-5μm range for the whole runs, so as to give an indication of overall filter performance.

Figure 5.12 shows the results of a 25% flow increase. What is immediately apparent is the good performance of alum at both temperatures. This concurs with previous experiments which suggest that a 25% flow increase is close to the lower threshold for causing additional breakthrough for alum.

Figure 5.12: Comparison of alum and PAX performance at different temperatures, during a 25% flow increase after 4h. (5m/h starting flow rate, 1m mono-media bed.)
It also shows that PAX is not as effective in reducing breakthrough under these experimental conditions.

This is especially the case with PAX at 14°C, although this high total is due to end-of-run breakthrough, not just during the flow change itself.

![2-5um breakthrough at different water temperatures (50% flow change after 4h)](image)

5.13: Comparison of alum and PAX performance at different temperatures, during a 50% flow increase after 4h. (5m/h starting flow rate, 1m mono-media bed)

Figure 5.13 shows a similar graph, with a flow change of 50%. The graph clearly shows again the superior performance of alum at colder temperatures, with a much reduced level of breakthrough. The results of the PAX experiments at 50% concur with published literature (Matsui et al. 1998, Exall and Vanloon, 2000; Gregory and Rossi, 2001) in that it is largely unaffected by water temperature, with both runs resulting in almost identical particle shedding. However, where these results differ is in the actual levels themselves, as the amount of breakthrough is far higher than the cold alum experiments.

The worst conditions for breakthrough were a combination of warm influent water and alum coagulant. This was largely expected given the trends from the previous
laboratory results using 50% increases, despite the previous graph showing such good performance for this variable at 25%.

5.1.3: PDA 2000 investigation

The variation in performance between PAX and alum at different temperatures was further highlighted when investigations were made using the PDA 2000 (Rank Brothers. Cambridge). Optimum doses of alum and PAX were used in 1 l of 10mg/l kaolin suspension. Each sample was rapidly stirred for 10 seconds to begin flocculation, and then stirred more slowly for 10 minutes (which correlated to the column retention time.). Rapid stirring for 5 minutes simulated the extra shear encountered during a flow change. The final 10 minutes of slow stir was designed to investigate what degree of floc recovery and regrowth was possible. The actual stirring rate increase produced a shearing rate which was actually much higher than that experienced in the laboratory column, due to the paddle size and rotation speed, and so was used as an exaggerated representation of the floc behaviour.

Figure 5.14 below shows the floc development of all of the variables tested, i.e. PAX and alum at 10, 18 and 25°C. The floc size is expressed as a flocculation ratio, which has been previously explained in chapter 2.10 and by Gregory (1999). It can be seen that for all of the temperature variables, the maximum floc development during the initial growth phase is greater when using PAX. Both alum and PAX display larger floc growth at higher temperatures (which was expected given the previous jar tests), and at the lowest temperatures the growth rate for both is fairly slow and the floc growth had not peaked before the stirring rate was increased.
With all of the variables, once the stir rate was increased the flocs were immediately broken up and greatly reduced in size. After the initial break up, the flocs continued to reduce in size, but at a much slower rate for the remainder of the rapid stirring period.

This correlates well with published theories reported as early as 1979 by Tambo and Hozumi, and also by Yukselen and Gregory in 2002, which suggest a 2 stage floc disintegration. The first being the break up of entire flocs, and the second being the erosion around the edges of the remaining flocs.

Once the stir rate was reduced, some limited floc regrowth was observed for each variable, but not to the same extent as the initial growth period. For all temperature variations, the regrowth was higher when alum was used as the coagulant, in fact the
experiment that displayed the most regrowth compared to its original floc size was alum at 10°C.

This suggests that alum at cold temperatures is the least affected, or most able to adapt and recover from increased shearing. This would support the results showed in figures 5.12 and 5.13, showing that the overall breakthrough is comparatively low using alum at 14°C, throughout the entire run. Even at 18°C, the regrowth of alum flocs is far greater than the PAX flocs.

During the PDA experiments, the particle counter was also used to monitor individual floc sizes during the phases of growth and destruction. Figure 5.15 below shows the size distribution of floc growth when using PAX at 10°C. This graph clearly shows the three phases of the floc development, with the largest particle size, >15μm rapidly increasing and peaking during the initial growth phase and thus causing the smaller sizes to decrease as the particles were agglomerated into the flocs. During the rapid stir period, the number of flocs in the largest size range is rapidly reduced as the flocs are broken up, and consequently there is an increase in the numbers of smaller flocs. Once the stir rate is reduced again, the numbers of flocs in the 7-10 and 10-15μm range continue to increase as the flocs begin to reform.
The numbers in the largest size continue to reduce, which was expected as there is no evidence of floc regrowth to the same magnitude as before the break up. This helps to support the theory of gradual erosion of fragile flocs after an increase in shear. This pattern was observed for all of the variables tested, with both alum and PAX producing similar proportions of flocs in each size range, and both displaying a higher number of >15μm sized flocs and lower numbers of 2-3μm flocs at 25°C compared to 10°C.

5.1.4: Shear stresses

The final investigation that was made into the variation in breakthrough at different temperatures was to examine the shear stresses within the filter. Using equations reported in Ives and Fitzpatrick (1989), theoretical shear stresses encountered within
the filter at different temperatures, flow rates and solid loading could be calculated. These calculations do not take into account the local pore geometry so can only be used as approximations of the forces experienced, but for this purpose they are sufficient to highlight differences at higher temperatures.

To simulate the clogging effect of using 10mg/L kaolin suspension, the media porosity was reduced by 0.002 per hour from the starting sand porosity of 0.4. This value was chosen arbitrarily, and although the resultant shear stresses are reasonable, further investigation would be required to refine the porosity value further. Table 5.3 displays the shear stresses encountered during 25, 50 and 100% flow increases after 1, 4, 7 and 20h at 15, 20 and 25°C, using the equations below.

Power/Fluid volume: \( \frac{P}{V} = \rho \frac{Q}{\varepsilon A L} \)

Maximum shear stress: \( \frac{3}{2} \left( \frac{P}{\mu V} \right)^{1/2} \)

Where \( \rho \) = water density (kg m\(^{-3}\))
\( \mu \) = water viscosity (N s m\(^{-2}\))
\( V \) = water volume in filter pores (m\(^3\))

<table>
<thead>
<tr>
<th>Flow Rate m/h</th>
<th>Time</th>
<th>15°C</th>
<th>20°C</th>
<th>25°C</th>
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<td></td>
<td>0.22</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>7.5</td>
<td>1h</td>
<td>0.26</td>
<td>0.23</td>
<td>0.20</td>
</tr>
<tr>
<td>10</td>
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<td>0.35</td>
<td>0.31</td>
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<tr>
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<td></td>
<td>0.23</td>
<td>0.20</td>
<td>0.18</td>
</tr>
<tr>
<td>7.5</td>
<td>4h</td>
<td>0.27</td>
<td>0.24</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.36</td>
<td>0.32</td>
<td>0.28</td>
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<td></td>
<td>0.46</td>
<td>0.41</td>
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</tr>
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</table>

Table 5.3: Maximum shear stress values (Nm\(^{-3}\)) during flow changes
The values give an idea of how shear stress varies with temperature, with the least shear stress observed during early flow changes at high water temperatures. The values range from 0.17Nm$^{-2}$ during a 25% flow change after 1 hour at 25°C, to 0.47Nm$^{-2}$ during a 100% flow change after 20 hours at 15°C.

It can be seen that for an identical flow change, but at different water temperatures, the shear stress acting upon the pore sediment can vary by 22%. For example a 50% flow change after 4 hours will produce a shear stress of 0.27Nm$^{-2}$ at 15°C but only 0.21Nm$^{-2}$ at 25°C.

Given these figures, it would be logical to assume that flocs need to be more than 20% stronger to overcome the additional shear stress experienced at the lower temperatures in the laboratory experiments.

When these shear stress values are compared with the visual observations of the floc development during the jar tests, it can be seen that although flocs created with alum at cold temperatures are smaller, they are not necessarily weak. That they can overcome the additional 22% shear stress levels and still perform better than the flocs at higher temperatures proves that they are strong. This contradicts some published literature (Hanson and Cleasby, 1990; Gregory and Rossi, 2001) which suggests that for a given shear rate, the larger flocs should be stronger, as the bonds within the flocs resist break up.

Overall, these investigations into the effects of temperature on filter performance, using a combination of techniques, have proved to be most beneficial in highlighting
the superior performance of alum at cold temperatures. This result is interesting in
it contradicts all previous published literature, which has advocated against the use of alum at cold temperatures. It may be that these findings can only be applicable for certain laboratory conditions, but the correlation between the different methods of examining floc growth and filter performance do indicate that these are true, accurate conclusions.

This study has also confirmed to a certain extent, the stability of PAX at a range of temperatures, with similar floc development at lower temperatures, and despite the poorer performance during a 25% flow increase at the lower temperature, this was not observed during the larger flow increases. It would appear that as a settling/clarification stage is not involved in this study, the need for more rapid settling of the flocs immediately after the coagulant mixing is required. This would explain why the alum outperforms PAX, as at colder temperatures the final residual turbidity shown in the jar tests was much less when using alum.

These experiments have illustrated the need for careful, site specific consideration when determining what coagulant should be used, as it seems that alum performs well during direct filtration, even at colder temperatures. PAX however would possibly benefit from a clarification stage, after which the performance may improve for all temperatures.
5.2) **Vibration effects**

Another cause of particle breakthrough, in addition to flow rate changes, was found to be vibrations that occurred close to the filter. This is a little researched phenomena, but in this study, it was found to be a major cause of particle shedding unrelated to flow changes. It was first observed during the laboratory experiments, whereby the breakthrough profile was disturbed during periods of construction work on the floor above. Unfortunately, no quantifying measurements were taken for further comparison.

![Comparison of breakthrough during static and vibration conditions.](image)

**Figure 5.21: The effects of vibrations on particle breakthrough in the laboratory**

Figure 5.21 shows the difference in breakthrough between identical filter runs, one of which was during the disturbances. A 100% flow increase was performed after 4 hours, and in this graph, only a 2 hour segment of the run is illustrated. It can be seen that although the breakthrough spikes during the actual flow change are very similar for both runs, the base counts of the disturbed run are higher preceding the flow increase. This is especially true of the 2-5μm size range.
The levels of breakthrough are far more unstable during the vibrations, and this filter run is unable to recover after the flow change, with increasing levels of breakthrough.

This was initially thought to be an anomalous set of results, and was not attributed to the vibrations, as the construction work was on a different floor. However, the same effects were then seen at one of the full scale plants during the period of data collection. The plant contractors were demolishing the decommissioned clarifiers, which were in close proximity to one end of the bank of filters. During the study mechanical equipment moved in and as a result, vibrations were transferred to the filters. The following graph, figure 5.22 illustrates the amount of breakthrough recorded from one filter at plant Y. The demolition work started on the 25th October and was carried out between the hours of 8am to 4pm. The impacts of these vibrations are obvious, with particle breakthrough in both size ranges rapidly increasing, and remaining raised for significant periods of time.

![Particle breakthrough during demolition work](image-url)

Figure 5.22: Particle breakthrough during demolition work at plant Y.
Although this filter was at the end of the bank, and as a result closest to the demolition, it still shows a worrying increase in breakthrough and was not a result envisaged by the plant operators.

It was not the intention of this study to purposely investigate the effects of vibrations on filter performance, but fortunately the building work during both the laboratory and full-scale research have provided such an opportunity. The results display conclusive evidence that vibrations occurring in close proximity to filters can have a serious detrimental effect to the filter performance. At both scales, particle breakthrough was higher and more unpredictable during the disturbances, and this must be a major consideration to water treatment plants when planning structural modifications, or anything else which may cause such vibrations.

5.3: Summary

This chapter has highlighted some causes behind particle breakthrough which are mostly unrelated to flow rate changes (the exception being shear stress, which is not in itself an external factor). It can be seen that these can be equally important in determining the amount of shedding from a filter, and must be an important consideration in any predictive models of breakthrough. The main findings of these experiments are;

- The influent water temperature plays a vital role in the overall filter performance
- The temperature of the water can increase or counteract the amount of particle shedding, during both stable operation and during flow changes.
• For these laboratory conditions, alum has shown to outperform PAX at lower temperatures, and results in reduced particle breakthrough during flow changes.

• One variable not investigated however, was the pH of the influent suspensions, which may have had a considerable effect on the overall filter performance. This would require a detailed study, as there are many associated factors to consider.

• Vibrations that occur in close proximity to the filters can cause a prolonged reduction in the stability of the filter, and higher rates of shedding.

It can be seen that both influent temperature and the effects of vibrations can greatly affect the amount of breakthrough that occurs during both stable operation, and during flow increases. These must be taken into account and the coagulant chosen carefully if particle breakthrough is to be minimised during flow changes.
6 Full Scale Plant studies

In order to investigate how flow changes can affect the filtrate quality at full-scale plants, 3 months were spent at three different water treatment works. These were projects carried out in conjunction with Dwr Cymru (Welsh Water), and so the works chosen were Plant X in West Wales, Plant Y in Hereford and Plant Z in Monmouthshire. As the conditions and existing problems differed for each plant, they shall be detailed individually in the chapter, as complete project reports. The investigations at these plants provided an excellent comparison with the breakthrough characteristics observed in the laboratory. They also allowed the monitoring of any additional causes of particle shedding.

6.1: Plant X Water treatment works

Plant X WTW in located in West Wales. It has the capacity to treat 50Ml/d, and is currently running at approximately 38Ml/d. Raw water is pumped from two sources into an on-site reservoir. Originally operated as a direct filtration plant, clarifiers were installed in the 1980’s. These, however, caused a deterioration of the water going onto the filters and so were decommissioned. A DAF plant was constructed in 1998 and this has dramatically improved the clarified water quality. The turbidity is now less than 1NTU, with Al less than 0.3mg/l.

There are 8 dual media rapid gravity filters which have the following configuration: 150mm gravel, 500mm sand (0.5-1.0mm) and 250mm Anthracite (1.18-2.36).
4 of the filters have been refurbished (filters 1, 5, 6 and 7) with nozzles set into the floor. The remaining old filters have laterals with holes (no nozzles).

The run time of the filters was 120h, although during this study, the cycle was reduced first to 110h and then to 100h.

This WTW has been the focus of several studies concerning the filter performance and various measures have already been implemented to improve water quality. These include the refurbishment of several filters, the installation of drain down siphons and a change in backwashing practices.

The aim of this 4 week study was to evaluate the filter performance in terms of particle breakthrough, and to decide whether the filter cycles were too long to ensure high filtrate quality. This was carried out during June 2001. Special attention was given to filter 1, as this had previously had the worst performance, and was offline for repair for most of the duration of the study. As a result, the hypotheses to be tested at the plant were:

"Particle breakthrough may be reduced by shortening the run time"

"Combined particle counts mask potentially harmful spikes on individual filters"

6.1.1: Methodology

2 particle counters have been used on individual filters to assess particle breakthrough during flow changes and also to compare performance between individual filters and the combined filtrate particle counter.
Particle sampling was set for every 2 minutes during the day, and every 5 minutes overnight. The duration of count was 1 minute. Over the weekend however, to keep within the 250 data limit, the duration was set to 5 minutes every 15 minutes.

A pilot column was also set up to assess the performance of a mono-media bed (in this case 0.5-1.0mm sand). However, the only electronic data collection was the particle counter so flow fluctuations during the night would not have been recorded.

Filter statistics:

- Average flow through the filter: 5m/h (50l/s)
- Water Temperature: 12.2-16.0°C
- pH range (clarified water): 6.8-7.2
- Run time: 110h week 1, 100h week 2.
- Media configuration: 250mm Anthracite, 500mm Sand, and 150mm Gravel
- Backwash: 2 minutes air scour followed by 4 minutes water wash 20% bed expansion
- Coagulation: 0.419 l/min Aluminium sulphate. 25.6mg/l as Al.

6.1.2: Pilot column statistics

- Height: 1.2m
- I.D: 90mm
- Flow rate: 5m/h (31 l/h)
- Run times: 100h
- Media configuration: 570mm Sand (0.5-1.0mm), 170mm Gravel
- Backwash: 2 minutes air scour followed by 4 minutes water wash 20% bed expansion
- Coagulation: 0.419 l/min Aluminium sulphate. 25.6mg/l as Al.

6.1.3: Filter 1 history

Prior to this study, the performance of filter 1 had been of some concern and the run time shortened to 60h. However, the quality deteriorated to the extent that the repair
The schedule was brought forward and during the study itself, filter 1 was refurbished and brought back online.

This involved excavating the media and then capping the majority of the nozzles, leaving just a few rows open. The media that had then been blocking the nozzles and collecting in the laterals was then removed using vigorous water and air scour. A surprisingly large amount of sand was removed in this way, considering the nozzles should have prevented any sand transport.

Once the sand had been removed and the air scour pattern was satisfactory, new media was replaced using the same configuration. The filter came back online on the 22\textsuperscript{nd} June and a 100h run was monitored during the last week of the study.

### 6.1.4: External factors

These factors were recorded as a means of potentially explaining particle breakthrough unrelated to flow changes.

- Filter 1 offline (6-22\textsuperscript{nd} June 2001)
- CelVac vacuuming media out of Filter 1 (week 1, possible vibrations)
- Air scour and cleaning of Filter 1 possibly caused more vibrations and delayed backwashing of other filters (increasing the duration of flow change in the remaining filters)
- Flow increases in the remaining filters increased from 14 to 17\% (flow split between 6 filters rather than 7)
6.1.5: Backwashing observations

Previous studies at the plant have raised concerns about the efficiency of the backwashing process, so filters that backwashed during working hours were observed. Of the filters which have been monitored, filters 4 and 8 performed satisfactorily, but filters 6 and especially 5 and 7 displayed uneven backwashing, with one side over spilling up to 14 seconds before the other. This suggests that the bed may be clogged as the water is unable to move up through the bed as quickly. Backwashing is ineffective in some cases and may lead to poorer subsequent filter performance. Once back online, filter 1 showed satisfactory backwashing.

6.1.6: Results

For graphical simplicity, as with the laboratory results, the particle breakthrough has been grouped into the 2-5 and larger than 5 micron range, as these represent both the *Cryptosporidium* size range, and also larger flocs which may harbour the oocysts.

**Performance of original filters**

Figure 6.11 show the end of run performance of filters 2, 3, 4 and 8, none of which have been refurbished. There are several spikes which are unrelated to flow increases, some of which are serious (>100 counts 2-5μm/ml). These are very short lived however, and do not tend to show up on the turbidity readings. There is seemingly no reduction in general water quality towards the end of the run, as the gradient of the particle count trend does not increase. F8 has most breakthrough, although becomes
more stable in the last 12h. Filter 2 has the best performance, with only 1 increase in breakthrough above 10 counts /ml. This was due to the dosing being taken off the automatic system, whereby the influent and final turbidity quickly rose. This illustrates the importance of correct chemical dosing, and how sensitive the system is to such changes. Once the correct dosing had been restored, the particle counts dropped back to the base level. This was correlated by a similar breakthrough trend in the pilot column which was running during the same period. However, despite this, the counts /ml were still far lower than some of the more random spikes, or even those displayed during flow changes in some of the other filters. This suggests that there are no problems with this filter and it is operating very well.
Figure 6.11: Plant X non-refurbished filter performance, last 30-50h of filter run. Flow rate 5m/h
Refurbished filter performance:

Figure 6.12 display the performance of filters 5, 6 and 7, which have all been refurbished. Only filter 6 displays good overall performance, with the exception of 1 large spike. This coincided with the vigorous air blasting of filter 1 in order to remove sand from the under drains. Both filters 5 and 7, as previously mentioned have poorer backwashing, which may result in the greater number of breakthrough spikes. F5 also has a higher proportion of large particle breakthrough, i.e. those above 5 microns. This could be more serious as the floc could contain both Cryptosporidium and also larger pathogens, e.g. Giardia.
Figure 6.12: Plant X Refurbished filter performance. Last 30-70h of filter run.
Flow rate 5m/h
Complete filter cycle performance:

Figure 6.13 shows 3 complete filter runs, to establish the overall performance of the filter, and whether the breakthrough spikes are more significant towards the end of the filter cycle. All filters assessed have been refurbished.

The graphs, especially filter 6, illustrate the importance of the sampling frequency of the particle counter, with less, and smaller spikes being observed over the weekend, as it is likely that particles were missed during each 10 minutes of unmonitored flow.

Filter 5 is more susceptible to breakthrough during flow changes, although there is no pattern between the magnitude of breakthrough and time of the flow changes within the filter cycle.

Filter 1 was running satisfactorily, with low particle counts during normal operation. The exception to this is the huge breakthrough that occurred during a period of coagulant failure. Once this was corrected, it did not take long for the filter to recover. This cycle also suffered a storm, which temporarily shut down the plant, and a shut down for maintenance. These are all illustrated by the drop in flow.

The combined filtrate particle counts have been included in these graphs, and whereas in general the breakthrough follows the same trend, the combined counter misses some spikes on the individual filters. This is likely to be due to the combined counts reducing these peaks to insignificant levels.

It appears that overall, the spikes that occur late in the filter cycle are no more significant than those observed during the main body of the run. This suggests that for these filters, the 100h run duration is not causing a serious breakthrough risk.
Figure 6.13: Breakthrough during entire filter cycles (100h) Flow rate 5m/h
Filter comparison:

Figure 6.14 illustrate the differences in breakthrough during what should be identical flow regimes.

The first graph, compares filters 5 and 8, i.e. old and refurbished filters, run in parallel during the last 30h of F8 cycle. Only the periods of filter backwash have been displayed, as it would be confusing to display the individual flow regimes of both filters.

Some of the breakthrough peaks match up, but each individual filter has its own spikes unrelated to either the flow changes or to each other, and these are likely to be missed by a turbidimeter or a longer counting interval. Although filter 8 has not been refurbished the performance is similar to that of filter 5.

The second graph directly compares performance between 2 new filters, 6 and 7. Filter 6 displays stable performance, with very few spikes, and only one above 100/ml.

Pilot column performance:

Figure 6.15 shows the performance of the pilot column. 2 runs, one of 100h and one of 72h. The column appears to be more sensitive to changes in the flow and influent conditions, whereby once disturbed, the column takes longer to recover to acceptable breakthrough levels. The flow changes later in the filter cycle cause more breakthrough than early increases, but the most influential parameter is the influent water quality. At the end of the first run, when the dosing was being done manually, and possibly not at the correct level, the influent turbidity rose to 1NTU and the
effluent quality was subsequently reduced. A similar incident occurred during run 2, whereby the alum dosing failed and the influent turbidity rose to 4NTU. This was possibly more than the column could withstand and the loading caused the flow rate to drop to unacceptable levels and so the run was stopped.

Figure 6.14: Comparison between individual filter performance, last 30h of filter cycle. Flow rate 5m/h
Figure 6.15: Particle breakthrough observed from pilot column, 72 and 100h cycles.

25% flow increases of 30 minutes duration upon flow rate of 5m/h (311/h)
Combined filtrate particle count data:

Figure 6.16 above shows the combined particle counts in the 2-5μm range. It clearly shows the increase in particle counts during each backwash, and also the benefit of reducing the counting frequency to 15 minutes from 1 hour. However, it does miss some crucial breakthrough events, such as that during the vibrations from filter 1, recorded by filter 6. This suggests that whilst it is beneficial to have a particle counter online, the sampling frequency must be set so that short term events are captured.

6.1.7: Filter 1 assessment

Although filter 1 is was back in service, it was replaced to exactly the same specifications as it was prior to blocking. This does not however, explain or treat the overall cause of it's bad performance. It is the writer’s opinion that it is not possible
that the amount of sand that was recovered from the laterals could have got there through damaged nozzles since the filter was originally refurbished and the nozzles put in place.

Possible causes of sand in laterals:

- The sand could have migrated into the laterals before the filter was refurbished and was not cleared before the nozzles were put in.
- Sand is being moved from the 3 unrefurbished filters on the same side (2,3,4) during backwashing. Whilst the sand can move up and down through the open filter floor in the old filters, any sand which moves down to filter 1 cannot re-enter the bed, and so could block the nozzles from underneath. Over time, this could accumulate to produce the quantities observed when clearing filter 1.

6.1.8: Conclusions for Plant X

- The overall filtrate quality is good.
- Flow changes caused an increase in breakthrough but this doesn’t increase with the time into the filter cycle.
- Particle count spikes appear which are not due to backwashing of adjacent filters. These were not picked up by the turbidimeter.
- Filters 2 and 6 gave the best performance of all the filters on site.
- There is not a great difference in performance between the old and refurbished filters
• 100h filter runs do not appear to significantly reduce water quality towards the end of the cycle.

• The combined particle counter accurately records most breakthrough events caused by the backwashing of individual filters. The increase in counting frequency to 15 minutes from 1 hour has greatly improved the usefulness of the data from the machine, but would still benefit from a further increase in counting frequency.

• Water quality should be carefully monitored during filter repairs, as vibrations caused during the repair of filter 1 may have caused several significant breakthrough spikes in the remaining filters.

6.1.9: Recommendations

• Run times at the site should be kept to 100h for the current water quality conditions

• The combined particle counter should be set to record at the bare minimum, every 15 minutes, preferably every 5 minutes, otherwise the data is inadequate.

• At this stage, there is no evidence to suggest that a change in media would benefit the WTW either economically or in terms of filtrate quality.

• If it is the case that the media from the un-refurbished filters are blocking the nozzles of the new filters, thus causing them to backwash poorly, it is recommended that they all be refurbished as soon as possible. This should improve the performance of the new filters, and may prevent the early spiking evident in the graphs.
If this is not the case, there is no evidence to suggest that refurbishing the filters will improve their performance. (Especially as combined air/water wash is not employed in the refurbished filters).

6.2: Plant Y Water treatment works

The second placement was carried out during September and October 2001 at Plant Y WTW, Hereford.

This treatment works is capable of treating 49Ml/d, and consists of 9 RGF’s preceded by ferric chloride coagulation and clarification. Originally there were only 7 filters, and these contained dual media (sand and anthracite), and have a side channel design for waterwash removal. The backwash process consisted of separate air scour and water wash. The 2 new filters were built to a slightly different design, and have a central channel for backwash removal. They have no anthracite or support gravel (only 0.5-1.0mm sand), but employ combined air and water backwash.

The aim at Plant Y was to examine the robustness of the filters in terms of particulate breakthrough, and in particular, whether flow changes caused by backwashing and low-lift pump operation cause excessive breakthrough.

Hence the hypothesis to be tested at this site was;

“Step flow changes caused by the low lift pumps and backwashing operation cause unacceptable breakthrough in the filters at Plant Y”
During the data collection, the decommissioned clarifiers were to be demolished, and as they were situated very close to the filters, the effects of vibrations were to be investigated, using the hypothesis;

“External vibrations cause unacceptable breakthrough in the filters”

The data was collected using 2 MetOne particle counters, which were connected to the turbidimeter outlet. The data was downloaded in real time to a software package which allowed a high frequency of counting (30-second intervals every minute). Entire filter runs have been monitored to examine the ripening period and also end of run breakthrough.

These counts were correlated to flow, turbidity, and headloss readings obtained from the SCADA system, along with information from the online combined particle counter.

6.2.1: Filter statistics

Average flow: 6m/h (50l/s)  
Run time: 24h (reduced on filters 8 & 9)  
Water temperature: 13-16°C  
Raw water turbidity: 4-22 NTU  
Settled water turbidity: 1.2-2.7 NTU

<table>
<thead>
<tr>
<th>Media configuration</th>
<th>Filters 1-7</th>
<th>Filters 8-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pea Gravel</td>
<td>100mm</td>
<td>0mm</td>
</tr>
<tr>
<td>1.0-2.0mm sand</td>
<td>100mm</td>
<td>0mm</td>
</tr>
<tr>
<td>0.5-1.0mm sand</td>
<td>600mm</td>
<td>800mm</td>
</tr>
<tr>
<td>Anthracite</td>
<td>150mm</td>
<td>0mm</td>
</tr>
<tr>
<td>TOTAL</td>
<td>950mm</td>
<td>800mm</td>
</tr>
</tbody>
</table>
6.2.2: Results

For graphical simplicity, the data has been grouped into 2 size ranges; 2-5μm and >5μm. This represents both the Cryptosporidium size range and also larger flocs, which could contain the pathogens. The numbers in the brackets on the graphs state which particle counter was used.

Comparison of particle counters

Figure 6.21 has been included to illustrate the problems that can arise when using particle counters. 3 particle counters have been used in this study, and all have been used on filter 1. The first graph shows breakthrough recorded on particle counter 1, and this was the only counter that could be relied upon to give accurate results. The second graph, produced using the second counter, appears to record a larger proportion of large particles (those above 5 microns). This is probably a result of the method of water collection, initially the water was collected in a well, out of which the sample was drawn. It is likely that if the sample was drawn from the bottom of the well, more settled particles will be extracted, thus distorting the particle size distribution of the sample. This has subsequently been fixed by attaching the input tube directly onto the turbidity outlet.

The final graph is completely unrealistic and is caused by air being sucked into the machine and causing the huge numbers of >5μm particles. This is a problem with the actual machine which required repair.

These graphs show that care must be taken when interpreting the results, as mechanical fault can give very misleading figures.
Fig. 6.21: Comparison of 3 different particle counters, to establish recording accuracy
Breakthrough in original filters

Figure 6.22 illustrates the breakthrough in a selection of the original filters. The first graph also includes the results of the combined particle counter, to compare breakthrough spikes.

All of the filters appear to have a lot of ‘noise’ in the count data. This is due to the high frequency of the counting, but it is likely to be genuine data as the counting period was long enough to exclude air bubble anomalies. All of the filters have serious breakthrough spikes of above 50 counts /ml, and there are many which exceed 100 counts /ml. It can be observed that some of the spikes are a result of filter washing, however, there are many events which cannot be attributed to flow changes, and are not easily explainable.

With the top graph (Filter 4), whereas the combined counter picked up the prolonged rise in base counts at 2pm, it did not record any of the larger spikes that occurred on the 19th Sept. This may have been due to the counting frequency of the machine, which recorded only every 5 minutes.

Overall, there appeared to be no defined ripening peak, possibly due to the high solid loading. Equally however, there was no deterioration in the filtrate quality of the filter towards the end of the filter cycle, and all of the original filters backwashed automatically on a time basis, rather than headloss or turbidity.
Fig 6.22: Breakthrough in original filters, entire filter runs (24h) Start flow rate 6m/h
Breakthrough during spate conditions

Figure 6.23 displays the filter performance during periods of unsettled weather and poor influent conditions from the river. Filter 3 (F3) had a huge number of serious breakthrough spikes (i.e. those above 100 counts /ml), especially those in the crucial 2-5μm range. These were mirrored by an increase in spikes on the combined particle counter. It also appears that during periods of higher settled turbidity, the ripening peak was more pronounced, as can be seen after the restart on the 29th Sept.

F4 shows the start of a small spate on the 2 October, with raw turbidity on the rise. This is matched by an increase in particle counts. Although there are few spikes above 100/ml, the worrying trend is that during the bad weather, the base line counts rise to approximately 50/ml suggesting larger amounts of breakthrough than if there were just short spike events. This is mirrored by the combined counter readings.

The main spate occurred between the 5-8th October. This is evident in the huge amount of breakthrough that occurred in F1. The huge scale of the graph indicates just how much breakthrough is occurring and this too is matched by the combined particle count data. The missing data overnight on the 6th and 8th Oct is due to software limitations rather than good water quality. This breakthrough came despite low settled turbidity, which is illustrated in table 6.1 in the general analysis section.

This worrying breakthrough suggests that the filters are not particularly robust during spate conditions, and careful monitoring must be made during such times.
Fig. 6.23: Filter performance during spate period (poor influent water quality)
Breakthrough in new filters

Figure 6.24 illustrates the breakthrough in the mono-media filters. It is immediately apparent that there are far fewer serious breakthrough events above 50 counts /ml. Again, not all of the spikes can be related to flow changes and the amount of breakthrough does not appear to be related to the proximity of the washing filter (possible vibrations).

The first graph, showing filter 8, also includes the combined particle counts for that time period. It can be seen that, unlike the original filters, the base line counts on F8 were actually lower than the combined counts. It is unclear whether the timers on both machines were synchronised, as the huge breakthrough event recorded at approximately 9am on F8, was either not picked up by the online counter, or that it’s clock was 15 minutes faster, as there does seem to be a similar event recorded at 8.45am. Both new filters display large breakthrough events during the actual backwashing of that filter, which was not seen with the original filters.

From a risk point of view, these filters perform better than the original filters, despite the shorter run times due to the massive headloss build up (which can be seen in Fig. 6.27a). This may be a combination of the wash regime and filter design rather than just a lack of anthracite, and if dual media was used in this design of filter, the headloss build up would be reduced due to the larger grain size of the anthracite.
Fig. 6.24: Breakthrough in new design filters. Entire filter runs, starting flow rate 6m/h. Fx denoted backwashing of each filter.
These graphs (Figure 6.25) show the impact vibrations can have on the overall water quality. During October, the decommissioned clarifiers were demolished. The machinery was operated between 08:00 and 17:00. The second graph in this figure
suggests that the vibrations caused by the demolition had a serious effect on the stability of the filters and large amounts of breakthrough were observed during this period.

This is despite the fact that F8 is more robust and had generally better performance than the other filters. (As shown in the 24th Sept graph of F8).

However, the weather and therefore the influent conditions were quite unsettled during the week commencing 24th Oct. This was taken into account when interpreting the data, for although F8 tends to cope well in spate, the extra solid loading may have contributed to the instability of the filter, and thus increased the breakthrough effects of the vibrations.

Ideally, (although not particularly practical) vibrations adjacent to the filters should be kept to a minimum, and if possible, not carried out during spate or other poor influent conditions so as to minimise the amount of breakthrough during vibrations.

**Breakthrough recorded by the combined counter**

The graphs in figure 6.26 each display 1 week of breakthrough events. The first graph initially appears to suffer far less breakthrough than the others, however, the counter had only been installed that week, and was recording on a far wider range, thus giving misleading results. It then counted in the range 0-200, which resulted in some spikes not recording their true value. It would appear, as shown when plotted on existing filter graphs, that the combined counter tracks the overall breakthrough very well, but that it frequently misses short term events. Altering the counting frequency of the machine could rectify this.
There was a great deal of breakthrough recorded overnight on Sunday 16\textsuperscript{th} Sept. Unfortunately, there was no individual particle counter data to compare to this, or indeed confirm that it was a serious breakthrough event.

The last graph is during spate conditions and shows large amounts of breakthrough, which were also recorded on the individual counters. This graph highlights very well the problems associated with the scale of the data collection. It currently only records counts in the range of 0-200/\text{ml}, which means that the true value of the breakthrough will not be recorded if it exceeds 200. This obviously causes problems in determining the seriousness of a breakthrough event. The only alternative is to set the counter to record in the range 0-2000. This however comes with its own problems in that much of the breakthrough detail will be lost.
Fig. 6.26: Breakthrough recorded on combined counter. 1 week of data per graph.
Comparison of headloss between old and new filters. No PAC

Comparison of Headloss between old and new filters: PAC added

Fig. 6.27a: Headloss build up during Powered Activated Carbon (PAC) addition

Comparison of headloss during spate conditions

Fig. 6.27b: Headloss build up during spate conditions for old and new filters
Comparison of headloss during PAC dosing

These final graphs (figure 6.27a) show headloss build up during two 48h periods, one before and one during powdered activated carbon (PAC) dosing. This was dosed to control a rise in humic levels. Both original (F4) and new (F8) filters are illustrated, and they appear to be in contradiction to the breakthrough graphs, which showed unaffected breakthrough levels during the dosing. It can be seen that before dosing, the run times are slightly reduced on F8, and this filter backwashes due to headloss limits being reached. However, the run times reach approximately 18h. However, during the dosing period, this reduces to such an extent that the run times on F8 are less than half that of F4. Despite this however, the filtrate quality remains good.

It is probable that the PAC forms a surface mat on F8, and strains the flocs rather than filtering them. Whereas the dual media filter is more able to cope with the PAC and distribute it within the bed, thus keeping the headloss down.

From an operational view point, the headloss build up on F8 is unacceptable, as it leads to very short run times and frequent washing, thus increasing water usage and in turn cost. However, as previously mentioned, from a risk point of view, the headloss build up does not correlate with increased particle breakthrough, and so does not pose a problem.

Headloss during spate conditions

Figure 6.27b shows the increased headloss build up during spate conditions. Similarly to PAC addition, the mono-media filter, F8 reaches terminal headloss much
quicker than the dual media filter, F4. It deteriorates to such an extent that during the height of the spate (5-6th Oct.) F8 runs times are reduced by half. Again, this is not reflected in the water quality of F8 and the particle count readings remain low.

It is likely that as the settled water quality actually improved during the spate (see table 1), the flocs must have become larger and settled onto the filter surface, thus forming a mat which rapidly increased the headloss. F4 still backwashed according to time, although with poorer performance over 24h.

6.2.3: Plant Y general analysis

The rapid gravity filters are just one stage of the treatment process, and it has been observed during this study that other processes are perhaps not working to their optimum capacity. Firstly are the clarifiers; despite reasonably low raw water NTU (during non-spate conditions), the settled water quality going onto the filter is relatively poor, up to 2.7NTU at times. This resulted in a very high solids loading of the filters.

Secondly is the backwash process; with such high amounts of particles in the bed after 24h, it appears the wash regime, (upflow rate and duration) combined with the side channel design, was not sufficient to remove all of the particles. This resulted in some of the flocs remaining in the filter and settling onto the media surface prior to the next cycle. This increased the solids held in the media bed, and over time poses serious breakthrough risks.
The 2 new filters did not suffer this problem as much because not only are they washed more frequently (thus less solids held in the bed), but also had a more efficient design and backwash regime.

During spate conditions, despite a sharp increase in raw water turbidity (which rose to a maximum of 287NTU during the study), the settled water quality going onto the filters actually improved during this time, as can be seen in table 6.1 below.

<table>
<thead>
<tr>
<th>Plant Y WTW wk 6</th>
<th>Raw Turbidity (NTU)</th>
<th>Settled Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday 8/10/01</td>
<td>287</td>
<td>0.4</td>
</tr>
<tr>
<td>Tuesday 9/10/01</td>
<td>143.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Wednesday 10/10/01</td>
<td>48.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Thursday 11/10/01</td>
<td>33.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Friday 12/10/01</td>
<td>42.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 6.1: Raw and settled water quality during spate conditions

This suggested 2 things. Firstly, during periods of poor water quality, the coagulant dosing was much higher and produced larger, denser flocs which rapidly settled onto the filter media surface, thus causing surface binding and, in the case of the dual media filters, poor effluent quality. Secondly, during periods of unsettled raw water quality, i.e. when the river is coming out of spate, the coagulant dosing was not optimised and this led to poor settled water quality going onto the filters. This in turn led to high solids loading throughout the filter bed and consequently more breakthrough. Another possibility is that the sub-optimal coagulation led to poor floc filterability, i.e. the flocs did not adhere to the media grains.

It would appear that in times of poorer raw water quality, a ripening peak was more evident at the start of the filter runs. Flow changes that occur before the filter has ripened have been observed to cause more breakthrough than during the main body of
the run. A solution to this problem would be to space out the washing regime of the filters, to ensure that filter washing does not occur during the ripening period of another filter. As filters 1-7 wash on time and not high turbidity, to create an hour after each backwash when no others can go to wash, would allow the first filter to ripen without detriment to the other filters, as 1 extra hour of filtration is unlikely to cause deterioration in the effluent quality.

It is possible that this plant was not designed to cope with the two extra RGF’s, and the different design of the new filters (and therefore shorter run times), causes far more flow changes in the remaining filters. When this is combined with the heavy solid loading, the breakthrough risk is higher, and as shown, resulted in frequent serious breakthrough events.

The addition of the PAC seemed to have made no impact on the water quality, (excluding the improvement in humic levels which were not part of this particular study) and the particle counts were not substantially higher during this period. The only effect was to further reduce the run times of the new filters.

The final point to raise concerns the “combined filtrate” particle counter. As the sample from each filter is collected into a communal pot before being fed into the Chemtrak counter, it is important that these samples do not become contaminated. As the lime dosing point is nearby, it was recommended that a cover be installed over the top of the collection pot, to eliminate any dust particles or chemicals artificially increasing the recorded particle counts. Also, with the recording range of the machine, a suggestion would be to set the range from 0-200 counts /ml during the
summer, as there are less spate conditions to record so the breakthrough trends can be seen in detail. During the winter, revert the range back to 0-2000 so as to record the true value of the breakthrough spikes during spates.

6.2.4: Conclusions

- Flow changes at plant scale do cause an increase in particle counts.
- The high solid loading may be responsible for the unrelated breakthrough spikes, possibly due to an “avalanche” process of the particles retained in the bed.
- Filters 1-7 are not very robust and perform badly during spate conditions
- Despite shorter run times, filters 8 & 9 perform better in terms of particle removal than the original filters.
- Vibrations appear to increase particle breakthrough on those filters in closest proximity to the source of vibrations.
- PAC addition made no detrimental impact to the water quality in terms of particle counts.
- The combined filtrate particle counter tracks overall breakthrough well and is a more useful and accurate tool than the turbidimeters in recording plant breakthrough performance.
- A cover on the collection pot of the combined counter is required so that false readings are not recorded.
- The wash regime of the original filters does not provide satisfactory cleaning and leaves a solids within the bed prior to the next cycle.
- Spacing out the filter washes (e.g. every 2-3 hours), may reduce breakthrough during ripening periods in spate conditions
These conclusions have been drawn from a range of influent conditions and external disruptions. It is possible that the performance of filters 8 and 9 deteriorates during serious spate conditions, but for the purposes of this study, they have proved to be the more efficient design in terms of reducing the potential risk of a *Cryptosporidium* outbreak, resulting from particulate passage through the filters.

6.3: Plant Z Water treatment works

Whilst the project was being carried out at the Plant Y WTW, it was possible to also investigate problems that were occurring at Plant Z WTW, as it was possible to reach both plants during the day.

Plant Z WTW is situated on the River Wye in South Wales. It has a license to abstract 5.5Mld but currently can only treat at 4.5Mld due to hydraulic limitations at the plant.

The works originally consisted of 3 RGFs preceded by solids contact clarifiers. These were refurbished in 1996 and the existing RGFs were converted into secondary GAC filters, and 5 new RGFs were built. These new filters are 9m² in plan area each, and contain 2 grades of sand (0.5-1.0mm and 0.6-1.2mm) supported by gravel media.

The filters are backwashed by separate air scour and water wash at rates of 42.5m/h and 25.6m/h respectively. This only provides 5% bed expansion.

It has been observed in previous studies that the quality of the water is so good coming off the clarifiers, that the filters have very little to remove, and as a result
struggle to remove the remaining particles. This is also thought to hinder ripening and thus leaving the filters susceptible to breakthrough during periods of poorer influent quality mid cycle.

The aim of this study was to investigate the effectiveness of the filters in terms of particulate removal, and also to determine whether 30 minutes is sufficient duration for the filter recycle process (i.e. the length of time when the filter effluent is returned to the filter inlet to be filtered again).

The hypotheses to be tested at this site are:

1) "Lack of filter ripening leads to increased breakthrough during the backwash of remaining filters"
2) "30 minutes is not the optimal duration of filter recycle for subsequent high filter efficiency"

Experiments used a MetOne particle counter on individual filters, which have recorded breakthrough during the 60h runs. The counting sequence for the machine was set to record for 30s every minute. This enabled a high resolution pattern of the breakthrough to be collected.

This data was compared to flow rates and raw and settled turbidity. Readings from the 2 online particle counters were also collected, but headloss data was not available.
6.3.1: Filter statistics

- Average flow: 5.1m/h
- Run time: 60h
- Water temperature: 11.5-13.5°C
- Raw turbidity: 7.5-103 NTU
- Raw pH: 7-7.71
- Coagulation: Ferric Chloride

Media configuration:

<table>
<thead>
<tr>
<th>Material</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>10mm Gravel</td>
<td>225mm</td>
</tr>
<tr>
<td>6mm gravel</td>
<td>150mm</td>
</tr>
<tr>
<td>0.6-1.2mm sand</td>
<td>375mm</td>
</tr>
<tr>
<td>0.5-1.0mm sand</td>
<td>250mm</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1000mm</td>
</tr>
</tbody>
</table>

6.3.2: Results

Although all size ranges between 2 and >15μm have been recorded, for graphical simplicity, the data has been grouped into the 2-5μm and >5μm size ranges. This represents both the Cryptosporidium size range, and larger flocs which could contain pathogens.

Unfortunately, due to software limitations and long run times, it was not always possible to record the entire filter cycle from backwash to backwash.

Breakthrough during complete runs of filters 1 and 2

The first graph in figure 6.31 shows the particle breakthrough during an entire 60h run in filter 1. The flow rate illustrates that there are fluctuations unrelated to filter backwashes, and these are likely to be due to changes in demand. A ripening peak is
very evident, which has a duration of approximately 5h in the 2-5μm range (the >5μm
type range ripens much more quickly).

The performance of the filter is very good, and there is no evidence of an increase in
breakthrough during the flow changes. The breakthrough appears to increase towards
the end of the filter run, despite a steady settled turbidity. However, this rise is only
comparative, as the maximum count of 12/ml is still very good.

The second graph shows the performance of filter 2 over a 5-day period, hence there
are far more flow changes. Again there are very distinct ripening peaks, and good
filter performance. For the first 36h of monitoring, the settled water quality is raised
at 1 NTU. However, this makes no impact on the filtrate particle counts, which
remain below 10 counts /ml (outside of the ripening peak). Examination of the flow
rate illustrates that this filter experienced flow changes of nearly 100% (from 6 to
11l/s). This is a very large increase and it is likely that such increases would cause
serious breakthrough problems during periods of high solids loading.

Particle breakthrough in filters 3 and 4.

Although figure 6.32 does not show entire filter cycles, the ripening peak following
backwashing is evident, and again these are of approximately 5h duration.

During the monitoring of filter 3, the settled turbidity rises to 2.77, during a short
period when the river was in spate. This however, does not cause an increase in
filtrate particle counts, which remain at a very low level. This suggests that the filters
are working well and can cope with poor influent conditions.

Filter 4 shows slightly poorer performance, with slightly raised levels of breakthrough
in the 2-5μm range, although again, the counts never rise above 13 /ml which is
acceptable. Not all of the flow data was available for the monitoring period of filter 4, which is evident by the cut off flow rate line.

Overall, the performance of all of the filters appear to be very good, with very little breakthrough, and none in response to flow changes.
Fig.6.31: Particle breakthrough in filters 1 & 2, entire filter runs (60h). Starting flow rate 5.1m/h
Fig. 6.32: Particle breakthrough in filters 3 & 4. 60h time period (incomplete filter runs) Starting flow rate 5.1m/h.
Breakthrough recorded on combined particle counters

Figure 6.33 shows the breakthrough recorded on the two online combined filtrate counters. One can record multi channel readings and is currently set to group the results into the 2-5μm and >5μm ranges. The second machine can only record total counts. As a result, this machine always shows more breakthrough on the graphs, as it is the total of each size group.

The first graph illustrates how close together the filter backwashes are, as shown by the large peaks. However, as the individual filter graphs show no response to the flow change in terms of increased particle counts, these combined peaks must come from the actual filter that has washed (i.e. the ripening peaks)

The second graph shows a slight deterioration in counts during the second half of the week, and this corresponds to the poorer performance seen on Filter 1 in Figure 6.31. It can be seen that this slightly poorer performance continues over the weekend (19th Oct.) but cannot be confirmed as no individual filter was being monitored during this time.

The final graph illustrates that the poorer performance continues until 23rd Oct. whereby the counts return to very acceptable levels, barely reaching 10 counts /ml outside of backwashing.

All of the graphs show that there is very little breakthrough of particles >5μm, and as such, the 2-5μm range on counter 1 and the total counts of machine 2 correlate closely. This is to be expected owing to the high efficiency of the clarifiers, which remove virtually all of the river suspended particles, and rapidly settle out the larger particles.
Fig. 6.33: Particle breakthrough measured on the combined filtrate particle counters: 1 weeks data
6.3.3: General Analysis

Overall, this study has illustrated that the filters are performing very well at Plant Z, and that breakthrough levels are very low. It would certainly appear that the filters are now ripening satisfactorily, and to extend the recycle period may not be beneficial, as the costs (wasted water and increased time of filter out of service) may outweigh the benefit of a more rapidly ripened filter, as there was no indication to suggest that the current ripening period was detrimental to the quality of the effluent.

The filter performance is not affected at all by flow changes, or by changes in the settled water quality. This is possibly due to the increase in coagulant dosing which occurred just before the study commenced. This may have optimised the process, and as such improved the overall treatment process. There is evidence to suggest that the particle counts may have substantially reduced since this change was implemented.

Given the results of this study, the only recommended change to the operational practices would be to space out the individual filter backwashes, as this may help to shorten the ripening peak, and stabilise the filters.

6.3.4: Conclusions

- The water quality after the first stage filters is very good, indicating an optimised clarification process.

- Flow changes do not increase particle breakthrough at this plant with good settled water quality.
• Increases in settled water turbidity do not result in poorer filter performance.

• 30 minutes is sufficient for recycle duration, and there would be no benefit in extending this period.

• The online combined counters monitor the filter performance very well, and are an accurate tool in assessing breakthrough levels.

There is no evidence in this study to suggest that any immediate action needs to be taken at this plant.

6.4: Full-scale plant general analysis

These projects at full scale plants have identified the same breakthrough trends as were generally observed in the laboratory. The first plant to be investigated, Plant X disproved previous ideas that filters should be backwashed every 24-48 hours to avoid poor performance. It was the case that these particular filters performed very well up to 100 hours, with no detectable end-of-run breakthrough. This may have been attributed to the exceptionally high quality water going on to the filters after the DAF process. The results coincide with the laboratory experiments in that flow changes do cause an increase in particle breakthrough, but in contrast, the full scale filters were not affected by the timing of the flow change. This plant also shows the effectiveness of dual media beds, which undoubtedly enabled such long filter run times without exceeding headloss parameters.
Plant Y WTW had the worst performing filters of all the plants investigated, but was overall a useful full scale study, which very closely related to the overall laboratory research. The filter cycle durations were (with the exception of filters 8 and 9), of the same duration to the laboratory experiments, which enabled direct comparisons to be made. It was clear that, as with the laboratory results, flow changes cause increased particle breakthrough, and that in most cases, flow changes that occur whilst the filter is ripening are more damaging in terms of particle shedding. This was observed with some of the 10mg/l kaolin laboratory experiments that were carried out at colder influent temperatures. The dangers of excessive vibrations in close proximity to the filters were confirmed. The increased breakthrough that was observed at this plant during the demolition work provided confirmation that the results observed in the laboratory could be genuinely due to the vibrations.

The results from Plant Y in general have shown that high quality water depends on all of the processes being optimised, as at this plant the coagulation dosing, backwash process and filter design were partly to blame for the poor performance of the filter, especially during spate conditions.

It would appear that the mono-media filters (numbers 8 and 9) outperformed the dual media filters in terms of particle breakthrough. However, this is more likely to be a function of the filter design and backwashing practices rather than the actual media, as the dual-media filters coped well with the PAC addition, whilst accumulating lower headlosses.
Plant Z highlighted how well mono media filters can perform when the preceding processes are optimised, and was the only plant that contradicted the laboratory results, as no additional breakthrough was observed during flow changes. Although the flow rate was identical to that used in the laboratory experiments, ferric chloride was used as the coagulant rather than alum, and the influent turbidities were different. Run times of 60h could be conducted with no end-of-run breakthrough and it would appear that the change in coagulant dosing prior to the study improved the ripening of the filters sufficiently to be able to cope with both flow changes and variations in influent water quality.

Overall, these projects have largely confirmed the laboratory results that flow changes do cause an increase in particle breakthrough, although outside of the ripening period, the timing of the flow change does not appear to be as significant. There were no significant water temperature changes at any plant during these projects, so the variable which was thought to be of importance in the laboratory results could not be tested. This would be a useful area of further research. The effects of vibrations however, were clearly demonstrated and should be a consideration for full-scale plant operators. These projects have also proved the advantage of particle counters, with far more detailed breakthrough being recorded on these machines than with the turbidimeters. However, it has also highlighted the need for careful analysis and calibration of the counters, as they must be set up carefully and correctly to ensure optimum performance, and false conclusions may be drawn from the results of an incorrectly installed machine.
In order to investigate what was happening to the flocs within the filter during a flow change, the high-speed video (HSV) was used in the laboratory.

A 1m bed of sand was used, as this media has been reported to provide the best colour contrast between the grains and the particles (Fitzpatrick 1993). Alum was chosen as the coagulant for this reason also. The camera was inserted into the bed, 0.1m from the top of the media (Deeper ports were not used as there were no visible flocs to record). Filter runs were performed using 10mg/l kaolin and 50% temporary flow changes were applied after 1 and 20 hours. Two influent water temperatures (16 and 25°C) were used to further assess the impact of temperature on floc behaviour. The filter was filmed at various stages, including the initial clean-bed grain orientation, the flow change itself and also the backwashing process.

It was found that with a flow change after 1 hour, sediment had not accumulated as far down the bed as the borescope at 0.1m depth. As a result, there was very little sediment detachment observed during the flow change. Some flocs were seen to move through the bed past the borescope during the first stages of the flow change, but these events were short lived and no re-attachment was observed.

When flow changes were applied after 20 hours, far more floc accumulation was observed. The video enclosed in appendix 4 illustrates two of the 20h flow change runs, one at each water temperature. The following descriptions of the 2 filter runs relate to the time code sequences of each stage of the flow change, which are found on the video itself.
7.1: **Observations of a 20h flow change at 25°C**

The initial scene of the video (Codes 004/ 00:40:000- 00:45:000) shows 30 seconds at the start of the filter run, and shows the location of the sand grains prior to any deposition. This would in theory provide an idea of where the flocs would be more likely to accumulate. However, the constant accumulation of sediment during the filter cycle has compacted the bed and caused the grains to move. This meant that the next scene could not be directly recognised as a continuation of the first scene as the grains were in a different position.

Scene codes 001 / 00:02:000 - 00:10:000 show the amount of sediment accumulation after 20 hours. It can be seen that there is a substantial floc "mountain" on each sand grain, as well as continual movement of individual flocs from the upper parts of the bed down through the media. The flocs themselves are quite large and woolly in appearance.

Scene codes 001 / 01:34:000 - 01:39:000 records the start of the flow increase. There is substantial floc detachment, with large flocs moving rapidly through the bed. Some of these flocs collide with the floc mountain in the middle of the screen and cause an avalanche. This can be seen in more detail during the section 001/00:39:000 - 00:39:450, which shows 2 seconds of the flow increase in slow motion, during which the process of individual floc detachment can be seen. However, much of the sediment actually remains on top of the grain. This may be because they are wedged against the glass plate of the borescope sleeve, or directly under the two grains above, which provide a certain amount of shelter from the increased shear stress. It is likely that a far larger shear rate would be required to remove the flocs from this location.
The velocity of the detached flocs during the period of increased flow rate was 18m/h (5\times10^{-3} \text{m/s}), despite the overall flow increase being only 7.5m/h (this was measured by replaying the video scene by scene, and measuring the distance travelled by the floc using the measuring rule on the video monitor). This is due to the decreased pore size due to the particle clogging, which increases the interstitial pore velocity.

The amount of floc detachment rapidly declined from the upper region of the bed, as expected, as most of the sediment was dislodged to the lower section of the bed. This was illustrated by the recording of the final minutes of the flow change. Scene codes 001 / 02:55:000 – 02:68:000 show that far fewer flocs are being detached from above, and the flocs themselves passing the borescope are much smaller. This too would be expected as during the flow change, floculation takes place under a higher shear, and so the flocs created would be smaller (Yukselen and Gregory, 2002(a)). There is also less time for floculation before reaching the media bed when the flow rate is increased.

The final scenes of this run illustrate the beginning of the backwashing process. Codes 003 / 00:22:000 – 00:51:00 show the first minute of the water only sequence. It can be seen that at first, individual flocs move up through the bed, which are then quickly followed by an uplifting of the grains themselves, as the bed begins to expand. It can be seen that the first media grains to pass the borescope are coated in alum flocs (003 / 00:25:500 – 00:37:000), but as the expansion continues the grains become cleaner. This suggests that after 20 hours the bed had become clogged to a certain depth, approximately 0.1m below the borescope, and also that the majority of this sediment is quickly removed during backwashing. The flocs themselves were
large and were often aggregated together, and these rapidly streamed past the media as the backwashing continued.

Overall, this recording has shown that after 20 hours of filtration, sediment had accumulated and clogged the bed to at least a depth of 0.2m. A 50% flow increase after such time causes substantial floc detachment from the upper section of the bed. At 25°C the flocs observed are large and woolly, but these decrease in size as the flow change progresses.

7.2: Observations of a 20h flow change at 16°C

The second filter run recorded on the video was a repeat of the previous experiment but at a water temperature of 16°C. The recorded sections follow a similar pattern, with the initial scene displaying the clean bed grain locations (001 / 00:24:000 – 00:28:000) Again though, after 20 hours the media has consolidated under the weight of the sediment and so the next scene has altered grain locations. Scene codes 001 / 00:02:000 – 00:15:000 show the amount of floc accumulation after 20 hours, and of the three grains in view, it can be seen that there is some floc coating on the tops of the grains. In this experiment, very little additional floc movement or detachment was observed. The 50% flow increase is applied at 001 / 00:37:000 and the comparison between the previous run is immediately obvious. The flocs are far smaller and are not detached from either the visible grains or the upper section of the bed in large numbers. The flocs that do detach and move through the bed do so at a much slower rate than the previous run (only 8.5m/h), which is closer to the overall flow increase rate of 7.5m/h. This suggests that the media pores are not as clogged,
and so the interstitial velocity is closer to the overall flow rate. This increases the opportunity for re-attachment, and would concur with particle count readings that breakthrough is reduced at lower temperatures. Scene codes 001/00:46:000 – 00:47:000 show a period of the flow increase in slow motion. It can be seen that there is very little evidence of individual floc detachment, with no avalanching of the existing particles. This is in contrast to the same experiment performed at 25°C, which displayed large amounts of detachment during the same period.

The next scene (002 / 00:08:000 – 00:15:000) shows the final minute of the flow change and it can be seen that, along with a reduction in floc movement, there is very little detachment from the three visible grains, and that some sediment may actually have re-attached to the bottom grain in the field of view.

The backwashing of this experiment was recorded, both the initial water wash and also the initial stages of the collapse-pulsing process. Scene 003 / 00:10:000 – 00:27:000 show again the upward movement of the individual flocs followed by the grains themselves, although in this case the flocs are much smaller and do not tend to aggregate. There is also no evidence of bed clogging or major coating of the media grains as they expanded. (This concurs with the previous calculations relating to the floc velocity through the pores).

Scene 004 / 00:00:300 – 00:10:000 illustrates the first stage of the collapse-pulsing process and it is obvious that the addition of air greatly affects the grain movement, as it is much more random and jerky. The air pulses themselves can be seen in and around the grains and it is this increased grain movement that improves the overall cleaning of the bed.
These experiments give an excellent indication of the processes that occur within the filter. They show what degree of floc accumulation occurs after certain periods of time, and then how much of the sediment is detached during a flow change. The recordings have shown again the importance of the influent water temperature, and it complements the growing evidence that although alum flocs produced at lower temperatures are smaller, the overall performance is better, with far less detachment occurring during the increase in shear caused by the flow change.
Having identified the breakthrough characteristics of the laboratory and full-scale filters under a range of process variables, the computer model Filterflex (Stevenson, 1997) was used to investigate the accuracy of the simulation in predicting the amount of particle shedding.

For every laboratory run carried out, a corresponding simulation was performed, altering the parameters accordingly. The basic theory of the model has previously been described in chapters 2.12 and 3.8 and the model parameters that could be altered are detailed in appendix 3.

8.1: 1m sand media simulation

The majority of the laboratory investigations were carried out on a 1m bed of 0.5-1.0mm sand, and so consequently most of the simulations were also set to these parameters. Temporary, permanent and gradual flow changes were applied after varying times into the cycle, and the graphs all illustrate the average residual concentration of the sediment, i.e. the percentage of sediment that is recorded in the effluent after the filter process. Individual size ranges of breakthrough are not recorded here, but the average concentration provides a good indication of the overall shedding. Unless otherwise stated, all of the simulations were performed at a water temperature of 16°C, as this is a more realistic influent temperature at full-scale plants.
8.1.1: Control runs

As with the experimental runs, it was important to identify the base line particle breakthrough for the filter, when no flow changes were being applied. Figure 8.11 below shows two control runs, at different influent temperatures (16 and 25°C). The runs were all of 24h duration, and the runs were simulated using a suspension concentration of 0.001 (so as to correlate to 10mg/l kaolin).

It can be seen that initially both filter runs have similar performance, with breakthrough levels just over 10%. However, as the runs progress, the performance of the colder run begins to deteriorate, whilst the warmer run remains fairly constant. By the end of the 24 hour simulation, the average breakthrough of the run at 16°C has risen to 14%. These results would be expected, with a higher viscosity at lower
temperatures creating higher shear stresses, and subsequent increased breakthrough. However, this was not what was experienced in the laboratory, with breakthrough levels actually lower when the influent temperature was lower, due to temperature affecting floc strength and structure.

8.1.2: Simulations using varying influent suspension

Figure 8.12 illustrates the important effect of the influent suspension on the filter performance. Two suspension values were used, 0.001 and 0.005, so as to simulate the two kaolin suspensions of 10 and 50mg/l.

![Graph showing simulated breakthrough using two concentrations of influent suspension, high and low.](image)

Fig. 8.12: simulated breakthrough using two concentrations of influent suspension, high and low. (5m/h flow rate, 1m mono-media bed)

It is immediately obvious that the simulation filter cannot cope with the higher concentration suspension, and satisfactory performance can only be maintained for just over 6h.
50% temporary flow increases were applied after 4h, and although both runs display a similar initial peak of breakthrough, the higher concentration run maintains a greater degree of shedding for the entire duration of the flow increase. With the lower concentration run, once the flow change has been completed, the filter recovers and performs well for the remainder of the run. The higher concentration run however increasingly begins to fail, and by the end of the 24h cycle, breakthrough approaches 100% (although the rate of shedding slows during the last 10h of the run.) For this reason, very few runs were performed at this high concentration. The remaining simulations detailed in this chapter are all performed using the lower concentration of 0.001.

8.1.3: Temporary flow changes

The first graph, figure 8.13, shows 50% temporary flow changes applied between 1-20h into the cycle. It can be seen that all runs display a sharp initial peak, followed by an extended period of breakthrough. The importance of the timing of the flow change can be seen, with more breakthrough occurring after 20h than after 1h. Also observed is the slight increase in shedding towards the end of the run, but this is still less than 15%.
50% temporary flow increases applied after 1,4,7 +20h (16C)

Figure 8.13: 50% temporary flow increases applied at varying times during the run (5m/h flow rate, 1m mono-media bed)

Also investigated was the effect of the magnitude of the flow change on the filter performance. Figure 8.14 illustrates the effects of 25, 50 and 100% flow changes applied after 4 hours. It can be seen that higher magnitude flow increases cause more particle breakthrough, seen both during the initial spike, and also in the amount of extended shedding during the rest of the flow change. Overall, the filter performs well for the remainder of the filter runs, with only a slight increase in shedding for all variables by the end of the cycle. These graphs also show the headloss accumulation during the runs, and all three show an increase in headloss during the flow change, which naturally increases with the magnitude of the flow change applied. The total headloss accumulated over the 24 hour cycle is similar for all three runs, with a maximum value of approximately 0.6m.

These graphs largely correspond to the laboratory results, with similar trends in breakthrough during flow changes with increasing time and magnitude.
Fig. 8.14: Flow changes of differing magnitudes applied after 4h
8.1.4: Permanent flow changes

Permanent flow changes of 50% were also applied to the model, and figure 8.15 shows the effects of these increases after 1, 4, 7 and 20h. It can be seen that the amount of breakthrough during the initial rise in flow increases with the timing of the flow increase, and that immediately after this initial spike, the filter begins to fail.

![50% permanent flow increases applied after 1, 4, 7 + 20h](image)

Fig. 8.15: 50% permanent flow increases applied at varying times during the cycle (5m/h flow rate 1m mono-media bed)

No simulation experienced any reduction in particle breakthrough once the flow had been increased. The early flow increases (1-7h) have a similar trend of shedding and rate of failure, with the earliest flow change causing the most breakthrough by the end of the cycle. This was not an effect observed in the laboratory experiments, with permanent flow changes not automatically causing a failure of the filter for all variables. It highlights some of the limitations of the model, whereby an increase in flow means that the shear conditions do not allow deposition.
8.1.5: Gradual flow changes

To simulate the gradual flow changes performed on the laboratory filter, step changes were built into the model to increase the rate of flow by 5% per minute. Figure 8.16 shows 50% gradual flow increases applied at various times during the filter cycle. As with the laboratory experiments, flow increases were of 30 minutes total duration, and the flow was reduced instantaneously.

![50% gradual flow increases applied after 1, 4, 7 + 20h](image)

**Fig. 8.16: 50% gradual increases applied to the model at varying times (5m/h flow rate, 1m mono-media bed)**

Again, the effects of timing can be seen, with more breakthrough occurring after 20h than after 1h. During the actual flow changes themselves, the actual breakthrough pattern is slightly different, in that there appears to be a large, but very short lived, spike, followed by a rounded secondary peak which lasts for the remainder of the flow change. This was only observed with the temporary flow change laboratory experiments, but suggests that it is a genuine phenomenon that can be explained by
the theory used in the model. After the flow change has been completed, there is a period of recovery and good performance before beginning to deteriorate slightly towards the end of the cycle. With the flow change after 20h however, the filter does not recover as well after the flow change, and breakthrough remains raised for the remainder of the filter run. All of the runs display miscellaneous breakthrough spikes, which increase in size throughout the run. These are short-lived events and are likely to be due to the evacuation of overloaded pores, an event which is built into the model. The amount of breakthrough observed during the flow changes is lower for each variable than the corresponding instantaneous temporary flow changes. This result was observed in several of the laboratory experiments, and was the desired result of introducing the flow change gradually.

8.2: Reduced bed depth simulations

When the bed depth was reduced to 0.6m, it can be seen that the overall performance of the filter declines. 50% temporary flow increases were applied after 1, 4, 7 and 20h and the breakthrough is illustrated in figure 8.21.

![Graph showing 50% temporary flow increases after 1, 4, 7 + 20h (reduced bed depth)](image)

Fig. 8.21: Temporary flow changes applied to a reduced media bed depth (0.6m)
It can be seen that the simulation cannot provide satisfactory performance with such a reduced bed, as the base line counts before the flow changes are closer to 20% breakthrough. The actual trends of breakthrough are very similar, with the later flow changes causing a larger amount of shedding. The initial spikes when the flow is first increased can be seen, which then reduce for each variable to a more stable (but raised) amount of breakthrough for the remainder of the flow change. After which, all variables display a degree of recovery, but in all cases, the base counts then continue to rise as the filter begins to fail. For all variables, by the end of the 24h cycle, the breakthrough levels approach 25%. Also observed are the random spikes seen in the previous graph (figure 8.16), and are thought to be a result of the same process.

Headloss values when using the reduced bed depth are lower than the 1m bed, with average maximum headloss values reaching 0.4m after 24 hours.

These results, to a certain extent, mirror the laboratory results, which found that timing was an important variable in determining the amount of breakthrough. However, the laboratory results displayed a far greater degree of failure after the flow changes, especially for a 50% increase in flow.

8.3: Simulations using a dual media bed configuration

Having completed the experiments using a sand only filter bed, investigations were made into the suitability of the model to predict dual media filter behaviour. The model was altered to contain the same media configuration as the dual media laboratory filter, for direct comparison, and the same flow changes were simulated.

All combinations were tested, but only one variable is detailed in this chapter. Figure 8.31 illustrates the effects of a 50% temporary flow increase after 1, 4, 7 and 20h.
50% temporary flow increase after 1, 4, 7 +20h (dual media)

**Fig. 8.31:** 50% temporary flow increases applied to a dual media bed (5m/h flow rate, 24h filter duration)

It can be seen that the filter actually performs slightly worse than the mono-media simulations in terms of base count breakthrough, with the residual concentration approximately 15%. The trend of increased breakthrough with time is evident, and the initial breakthrough spikes are higher than for mono-media when the flow is initially increased. However, these spikes rapidly decrease to leave an extended period of breakthrough that is actually lower than the mono-media experiments, for the remainder of the flow change. Recovery for all variables tested was good, and in this case, the end-of-run breakthrough levels were similar to those achieved in the sand simulations, at approximately 16%. These simulation runs also take longer to ripen than the mono-media experiments, which was not always the case with the laboratory experiments. The headloss accumulation for the dual media experiments was slightly less over the 24h duration than when using mono-media, with maximum values approaching 0.5m. This was expected due to the higher porosity and larger grain size of the anthracite on top.
These results differ slightly from those achieved in the laboratory, as the experiments showed that dual media performance was far superior to mono-media both in terms of base line counts and also resistance to breakthrough during flow changes and at the end of the cycle. However, they both agree that flow changes later in the run are more harmful.

8.3.1: 10m/h starting flow rate simulations

The laboratory experiments using dual-media indicated that the filter would be able to cope with an increased starting flow rate, and so both 10 and 7.5m/h were investigated. Using the Filterflex model, only a 10m/h starting rate was simulated, and figure 8.32 illustrates the effects of 25% temporary flow changes applied after 1, 4, 7 and 20h.

![Graph showing 25% temporary flow increases applied after 1, 4, 7 + 20h (10m/h start flow rate)](image)

Fig. 8.32: Temporary flow increases using a starting flow rate of 10m/h (dual media bed)
It was immediately apparent that the model filter cannot cope with the higher flow rate, and satisfactory particle removal could not be achieved. Even prior to the flow changes being applied, the base rate could only limit the shedding to 20%, which was maintained for approximately 2 hours. After this time, the filters all began to fail at a steady and similar rate. The effects of the flow changes themselves are different in that they caused proportionally less additional breakthrough as the cycle progressed. This meant that a 1h flow change caused a greater rise in particle counts from the base level than a 7 hour increase, but the overall percentage of shedding was higher after 7h because the base rate itself was higher. By 20 hours into the filter run, the base level was so high that the flow increase had no impact, and no additional breakthrough was seen. However, this may have been due to the model parameters, and by altering some values such as limiting shear, different results may have been observed. This is something that requires further research.

These simulations correspond to a certain extent to the laboratory results, which also could not maintain satisfactory performance for the duration of the filter run. However, the laboratory column could prevent particle breakthrough for approximately 11h before failing, whereas the simulation show failure more quickly. Also, the actual column experiments display the usual trend of increased breakthrough with time, with the early flow changes not causing a great deal of additional breakthrough.
8.4: Simulations using different influent temperatures

The final simulations performed were to investigate the importance of the influent water temperature on the filter performance, as it was clear that this was a very important variable to the laboratory experiments.

Figure 8.41 displays the effects of a 50% temporary flow increase after 4 hours. The two influent temperatures used were 16 and 25°C. This was achieved by altering the viscosity and water density in the model’s parameters.

![Graph showing 50% temporary flow increase after 4h using different influent temperatures](image)

Fig. 8.41: 50% temporary flow increases using different influent temperatures

(5m/h flow rate, 1m mono-media bed)

It can be seen that the run performed at the lower water temperature has a higher level of breakthrough, both during stable operation and also a much higher peak during the flow change. Although both runs showed an increase in shedding during the flow
change, and good recovery afterwards, the colder run showed more end-of-run breakthrough and miscellaneous short lived spikes.

This totally contradicts the results achieved in the laboratory, which displayed better performance at colder temperatures. This suggests that there are more processes occurring within the laboratory filter than are programmed into the model. An example of this is the suitability of the coagulant type and dose to the water conditions. Again, further research could involve altering more of the parameters within the model to compensate for these differences, such as reducing the floc size ratio to simulate smaller flocs at colder temperatures.

8.5: Summary

The use of the Filterflex model has provided a very good supplementary tool in predicting and analysing the performance of the filter under a range of process variables. To a large extent, the computer model has accurately matched the amounts and trends in breakthrough observed in the laboratory experiments, and helps to confirm the hypothesis that particle breakthrough increases with both time and magnitude of the flow change itself. It has also shown that gradual flow increases on the whole are a more suitable method of introducing the flow change, with a lower amount of additional breakthrough observed for all variables.

However, the model deviates from the laboratory results when dual media is used. The simulations suggest that mono-media provides superior performance in terms of breakthrough levels, whereas the laboratory results displayed the opposite. The model
also gave poorer performance using dual-media at higher flows than was observed in
the laboratory.

The final difference between the model and the laboratory results was observed when
considering the effects of influent temperature. Again, totally contradicting results
were obtained, with the model suggesting performance would be poorer at lower
temperatures, but the reverse being observed in the laboratory. This may be because
the model only allows the physical properties of the water to be altered, with no
consideration to the chemistry of the water and coagulant.

Overall, the model has proved to be fairly accurate when used to demonstrate the
amount of particulate breakthrough that would occur during flow changes on a mono-
media bed, and as such would provide a very good predictive tool. However, care
must be taken when using the model to predict dual-media behaviour, and also when
analysing the effects of influent temperature.


21 DISCUSSION

The experiments performed during this research have produced results at two scales, and provide a comprehensive investigation into the processes occurring within a filter during flow changes. The initial laboratory experiments have established patterns of breakthrough, some of which were expected, and others which required further investigation into the internal processes.

9.1: Laboratory filter runs

The first runs to be performed were 30-minute temporary flow increases above a starting flow rate of 5m/h. These were carried out on a 1m bed of sand, of grain size 0.5-1.0mm. When 50mg/l of kaolin was used as the influent suspension, several patterns of breakthrough were established. Firstly it could be seen that the higher the magnitude of flow change applied, the higher the amount of particle breakthrough was recorded. Also of importance was the timing of the flow change, with more breakthrough occurring during the increases applied later into the filter cycle. This correlated well with results from several researchers such as Cleasby et al. (1963), who produced the first major study on the effects of flow changes on filtration. They found in their laboratory experiments that flow changes of 100% caused over 22 times more breakthrough than flow increases of 25%. This is almost identical to some of the results achieved in the laboratory when using 50mg/l kaolin, whereby approximately 20 times more breakthrough was observed during flow changes after 7 hours.
Kau and Lawler (1995) also provided laboratory evidence of greater breakthrough with a higher magnitude of flow increase, and Fitzpatrick et al. (1999) confirmed this is also true at some full-scale plants.

In many of the runs, a secondary peak of breakthrough was evident during the flow change itself, especially during the higher magnitude runs. This could be attributed to the high amount of hydraulic loading on the filter, whereby the increase in shear detaches many flocs deeper into the bed, which then are increasingly removed into the effluent during the remainder of the flow change. The higher solid loading could also be responsible for the large amount of breakthrough in the >5μm range during the flow changes later in the run, as whole flocs are detached from the media when the flow is increased.

However, when the influent concentration was reduced to 10mg/l kaolin, the patterns were not as obvious. There was not an automatic increase in breakthrough with the timing of the flow change, with breakthrough during flow changes after 22h often recording similar amounts of shedding as those after just 1 hour. A possible explanation for this could be that the particles within the bed become more stable with time, and so more resistant to detachment. Also, the growth of biofilms during the filter cycle may increase the adhesion of the flocs to the media, as they are incorporated into the biofilm itself. Kaur et al. (2001) has found that biofilm growth can be significant within 24h in rapid gravity filters and so adds weight to the argument that biofilms may cause the reduction in detachment during flow changes very late in the filter cycle.

None of the filter cycles suffered any end-of-run breakthrough, and no secondary peaks were observed during the flow changes. These results highlight the importance of the influent suspension to the effectiveness of the filter, and for these laboratory
conditions, 50mg/l kaolin caused far more breakthrough than 10mg/l during flow changes for the same magnitude and time into the filter cycle. This concurs with Wilson and Morse (2002) who also found that the influent suspension was of great importance in the amount of breakthrough from the filter, and a high influent turbidity resulted in increased particle shedding, even during stable filter operation with no flow changes.

Permanent flow changes were applied to simulate a filter being taken offline for repair or an overall increase in demand. The 50mg/l kaolin experiments again showed a strong pattern of increased shedding with an increase in the magnitude of flow change applied, and in most cases end-of-run breakthrough was also observed. This was expected due to the prolonged duration of higher flow rates, and subsequent higher solid loading. However, no secondary peaks were observed after the initial breakthrough spike, and the breakthrough profile did not automatically suggest that the flow had been permanently raised, i.e. in many cases the particle counts reduced after the initial spike for several hours before failing at the end. This confirms a point put forward by Cleasby et al. (1963) who suggest that breakthrough is independent of the duration of the flow change. It was found that a flow change after 1 hour caused the most breakthrough, which was not expected and suggested other factors must be involved. An increase of 25% made very little impact to the breakthrough characteristics and appears to be close to the lower threshold for disturbing the filter, i.e. the increase in shear during these flow changes was not sufficient to overcome the attachment forces.
When 10mg/l kaolin was used as the influent suspension, some patterns remained, such as an increase in breakthrough with the magnitude of the flow change. However, no end-of-run breakthrough was observed, which might be expected due to the lower solid loading compared to the 50mg/l kaolin influent. Again, the 1 hour flow change caused the most amount of breakthrough, which suggested that the filter had not finished ripening. The most interesting result of the permanently introduced flow changes was that the actual amount of particle shedding was very similar between the two influent concentrations tested. It was expected, based on the previous results using temporary flow changes, that the higher influent concentration would cause far more particle shedding from the filter. However, the 50mg/l kaolin experiments were conducted during the winter and so the influent water temperature was lower. This is thought to be the main factor behind the similar breakthrough results. This is explained in more detail later in the chapter.

Recommendations by the Badenoch reports (1995 & 1998) suggested that any flow changes applied to a filter should be done gradually, and a rate of 5% per minute was recommended. This was investigated during this research and results using 50mg/l kaolin showed that the overall performance of the filter was better than when the flow changes were introduced instantaneously. There was no additional shedding when flow changes were introduced after 1 hour, and also no end-of-run breakthrough. All of the shedding spikes were lower in number than those observed during the initial temporary flow change experiments.

When the suspension was reduced to 10mg/l kaolin, the patterns of breakthrough were very similar to the temporary flow change experiments using the same concentration. This meant that more breakthrough was observed during flow changes applied after 7
hours than after 20 hours. The reasons for this pattern are thought to be the same as for the temporary flow changes, i.e. the increased stability of the particles within the filter and the increased incorporation of the flocs into biofilms with time. There was no end-of-run breakthrough for any variable, and also there was no pattern of increasing magnitudes of flow change causing more breakthrough. This is likely to be due to the slow introduction of the flow change, which meant the shear applied to the flocs was also increased gradually, and so may have caused the flocs to restructure rather than break off. These results have shown that the gradual introduction of flow changes is preferable to instantaneously introduced increases, as the particle breakthrough levels are reduced both during the flow disturbance itself, and also towards the end of the filter cycle. Logsdon et al. (2000) advocated the benefits of introducing flow increases gradually, and Cleasby et al. (1963) achieved similar results in the laboratory to those described here, with breakthrough levels being reduced when the flow was gradually introduced.

Experiments performed on a reduced bed depth of 0.6m used only the lower kaolin concentration of 10mg/l. High quality filtration could only be maintained for approximately 19 hours, after which the end-of-run breakthrough rapidly increased. The temporary, gradual and permanent flow changes applied all produced patterns of increased breakthrough with both magnitude and timing of the flow change. Kawamura (2001) recommend that when designing rapid gravity filters, the L/d ratio (where L = bed depth in mm and d = effective grain size in mm) should be used to establish an effective bed depth. For RGF’s the ratio should be greater than 1000. Using this ratio, a bed depth of 0.6m gives a result less than 1000, and so explains why the filter as a whole gives unsatisfactory performance and shorter filter run times.
Another reason for the poorer performance of the reduced bed depth filter has been highlighted by Cleasby et al. (1963). They state that shear forces are the dominant factor in particle detachment (this is also concluded by Ives and Fitzpatrick (1989) and observed in the video endoscopy work in this research). Once detached into the suspension, the flocs could only be re-deposited when the deposition forces overcome the detachment forces, for example further down the bed where there is a reduction in clogging. The lack of deposits mean the pore space is increased and therefore the interstitial velocities are reduced which decreases the shear. However, if the bed depth is reduced, there may not be a sufficient reduction in clogging to reduce the shear forces before the flocs pass into the effluent, and fewer grains available for attachment.

Surprisingly the gradually introduced flow changes on the 0.6m bed caused more breakthrough than both the instantaneously introduced temporary flow changes, and also the gradually introduced flow changes on the 1m bed depth. The reduced bed depth experiments were performed at a higher influent temperature than the experiments using a 1m deep bed, which again may account for these discrepancies, and the fact that the breakthrough patterns are more pronounced.

To research some of the observations seen at the full-scale plants, the laboratory filter column was altered to accommodate dual media. 0.5-1.0mm sand and grade 2 anthracite was used in the same configuration as one of the treatment plants. 50% was the only magnitude of flow increase investigated due to time constraints. Overall, the dual media filter provided excellent performance, with very low particle shedding during stable operation. The temporary flow change experiments produced the familiar pattern of increased breakthrough with the timing of the increase, but
these were short lived shedding events, and particle counts quickly returned to base levels. No end-of-run breakthrough was observed for any variable, and headloss development over the 24h period was less than that recorded during the mono-media experiments. This was an expected result, and suggested that the filter cycle could be extended in duration when dual media is used. This is confirmed by research by Yohe et al. (2002) whose experiments using dual media (sand/anthracite) yielded increased run times of 50% compared to mono-media sand. They also found that particulate removal in the 2-5μm range was increased by 20%.

The permanent flow changes produced a result similar to the mono-media experiments, in that a flow increase after 4 hours caused the least amount of additional breakthrough. This concurs with the suggestion that flow changes are least damaging during periods of stable filter operation, i.e. after ripening but before the filter accumulates too much solids.

When the flow changes were introduced gradually, the filter coped very well, with very little additional breakthrough during the flow changes, and very rapid recovery after the flow was returned to its original value. The headloss development was the lowest for all variables tested.

These results were very encouraging, suggesting that particulate breakthrough could be minimised for certain filter conditions. All of the dual media experiments were performed during the winter, and so again the influent water temperature was low, which may have contributed to the good performance of the filter.

Having recorded good performance from the dual media filter when the flow rate was permanently raised, it was thought that the filter would cope well with a higher starting flow rate of 10m/h. 25% temporary flow changes were applied on top of this
starting rate at varying times during the filter cycle. Overall, high quality filter performance could only be maintained for approximately 11 hours, before experiencing a very large amount of end-of-run breakthrough. The flow changes did not cause much additional shedding when applied after 1 and 4 hours, which further suggests that 25% may be at the lower threshold for disturbing the filter. However, as the filter was already failing by 20 hours into the cycle, the flow change after this time resulted in a large breakthrough spike.

Using 7.5m/h as a starting flow rate produced very similar results, with no additional breakthrough after 1 and 4 hours, and end-of-run breakthrough occurring after approximately 12h. Flow changes after 20 hours produced a larger amount of breakthrough in the >5μm range for both starting flow rates, which suggest a serious breakthrough event involving entire flocs which could contain Cryptosporidium oocysts or other pathogens.

With the higher starting flow rate of 10m/h, the same amount of water can be produced in 12h as a full 24h cycle at a starting flow rate of 5m/h. The compromise between rapid water production and increased backwashing frequency is one which must be taken into account at individual plant level.

All of the previously discussed experiments have been conducted using aluminium sulphate as the coagulant. However, as it became clear that the influent water temperature was an important variable in the efficiency of the filter, experiments were repeated using polyaluminium chloride (PAX), as it was reported to be unaffected by temperature (Matsui et al. (1998), Exall and Vanloon, (2000)). Temporary flow changes were applied to a 1m bed of sand, using 2 influent temperatures of 16°C and
25°C. The control runs showed that the base level particle counts were higher than when using alum, the headloss development was higher and the flow reduction was higher over a 24h period.

When the influent suspension was at 16°C, there appeared to be very little impact during the 25% flow increases in terms of additional shedding, but the run times were reduced by increased end-of-run breakthrough. The pattern of increased breakthrough with both time and magnitude was also observed. Overall, the performance of the filter when using PAX at the lower influent temperature was not as good when alum was used. This goes against much published literature which all state that PAX outperforms alum at cold temperatures (as low as 3-5°C), at both laboratory and full-scale (Matsui et al. (1998); Exall and Vanloon, (2000); Gregory and Rossi, (2001); Duan and Gregory, (2002)).

At 25°C, the base counts in the 2-5μm range were still high even during stable operation. 25% flow increases resulted in no additional breakthrough, but at 50% the flow changes were sufficient to cause an increase in breakthrough that increased with the timing of the flow change, and also resulted in end-of-run breakthrough. These results have shown that, in line with published literature (Exall and Vanloon, (2000)), PAX is not as temperature dependant as alum, with similar levels of breakthrough being observed at 16 and 25°C. However, the results have also shown that, for these laboratory conditions, the performance of PAX is worse than alum during stable operation, and also results in shorter filter runs.
9.2: External factors affecting filter performance

The reasons behind the non-uniform patterns of breakthrough were better understood when external variables such as water temperature and vibrations were investigated.

9.2.1: Temperature effects

During the course of this research, experiments were continually performed during the summer and winter, and it became clear that the influent water temperature (which naturally changed throughout the course of the year) played an important role in effecting the amount of breakthrough from the filter. Several different methods of analysing these effects were used to ascertain the extent of variance in magnitude of breakthrough between the temperatures.

Firstly, experiments were repeated using alum as the coagulant, and the influent water temperatures investigated were 16 and 25°C. Temporary flow changes were applied after 4 hours, and the difference in breakthrough levels was obvious. When the higher influent temperature was used, the particle shedding was much higher during the flow change itself, and the filter became far less robust after the flow was returned to its original value, with increasing end-of-run breakthrough. This was the case for all of the variables tested and indicated that alum was less efficient at warm temperatures. This is in direct contradiction to the results by several researchers, such as Hanson and Cleasby (1990), who found that the performance of alum as a coagulant was less efficient at cold temperatures.
Jar tests were performed to further investigate this phenomenon, and both PAX and alum were tested to observe floc growth at a range of temperatures. It was found that at 25°C, both alum and PAX displayed similar floc growth, with large and woolly flocs developing within a few minutes. As expected, lower temperatures produced smaller flocs for both coagulants, which took longer to develop. This has been confirmed by the results of several researchers such as Morris and Knocke (1984) and Hanson and Cleasby (1990) who produced similar results of slow floc formation at colder temperatures. However, the PAX coagulant was less dependent on temperature at lower temperatures, with very similar floc development at both 18 and 10°C. The PAX flocs did not display much settling during the final settling period, and as a result, the final turbidity was far higher than the corresponding alum results. This suggests that when PAX is used as a coagulant, a settling process before the filtration stage would be of benefit to the overall treatment performance. However, during the jar tests the only variable investigated was temperature. No analysis was made of alkalinity, pOH, or other chemical parameters which may have helped to explain the anomalous performance of the coagulants.

To further investigate the differences between these coagulants, experiments were performed with the influent temperature being the only variable. Temporary flow changes were performed using alum and PAX at both 14 and 24°C. The results confirmed several of the previous observations concerning the performance of the coagulants. It could be seen that alum performed very well at the colder influent temperature, although this temperature was only cold in terms of the laboratory conditions. This suggests that even a small range of temperatures can have a great affect on the overall filter performance. Contrary to published literature, the
performance of PAX was not as good at 14°C, in terms of increased particle breakthrough.

Also confirmed was the limited breakthrough observed during flow increases of 25%, when alum was used as the coagulant. This suggests there is a threshold for the magnitude of flow increases, below which the increased shear will not overcome the attachment forces of the flocs to the filter media. Several other researchers have found similar patterns of limited breakthrough, with flow changes <10% causing no additional breakthrough in the laboratory in the case of Cleasby et al. (1963), and Fitzpatrick et al. (1999) found increases of <30% had no major impact on breakthrough at full-scale plants, providing the filters were not too clogged. Jung et al. (1996) suggest the reason for this is that at low shear rates, flocs restructure rather than break up or detach. However, at higher shear rates flocs do break up, the implication being that large deposited flocs may break up, leaving some deposit on the grain, and some detached into the suspension.

When the magnitude of flow increase was increased to 50%, it could be seen that the performance of PAX was unaffected by the temperature of the influent, with very similar levels of breakthrough occurring at both 14 and 24°C. Also, at this magnitude of increase, the use of alum at the higher temperature resulted in the largest amount of particle shedding. This concurs with the previous laboratory results which suggested that the higher rate changes caused an increase in breakthrough.

The PDA 2000 was used to establish why alum should provide better performance at colder temperatures for these laboratory conditions.
showing slightly better re-growth than Alum. At the lowest temperature, the alum flocs displayed proportionally the highest degree of reformation, which suggests that alum flocs at cold temperatures are most able to recover from an increase in shear. This helps to explain why the experiments using alum at cold influent temperatures suffered the least additional breakthrough during flow increases.

Having established that alum flocs at cold influent temperatures appear to be able to better withstand an increase in shear, calculations were made to establish what the shear stress values acting upon the flocs in the filter were.

The calculations (detailed in chapter 5.1.5) revealed that flocs in a mono-media sand filter needed to be >20% stronger to overcome the increase in shear experienced at cold temperatures. This suggests that although the flocs developed using alum in colder influent temperatures are smaller, they are not necessarily weak, as they can withstand this extra shear and the filter overall performs well in terms of reduced shedding. This correlates to the conclusions drawn by Yeung and Pelton (1996) and Yeung et al. (1997), who found that there was no scaling relationship between floc size and floc strength, and that the conditions for optimal flocculation did not correspond to those of maximum floc strength. Although these conclusions were drawn for polymer based coagulants, it is suggested that the results could hold for other coagulants, and the idea of floc strength varying with shear rate during flocculation may replace previous multi-level floc structure models of primary particles growing to floc aggregates.

Overall, these additional investigations into the effects of influent temperature have developed an interesting pattern of superior performance of alum at reduced influent
At all temperatures, PAX flocs were observed to develop more rapidly and to a larger size than the corresponding alum flocs. This correlates with the jar test results, which showed that after the initial mixing period, the turbidity of the PAX suspension was lower (i.e. fewer but larger flocs). These results concur with those achieved by other researchers using the PDA 2000, for example Gregory and Rossi, (2001) and Gregory and Yukselen (2002b) who all reported the rapid and large growth of PAX flocs. Also, corresponding to the jar tests was the fact that at higher temperatures, both coagulants developed larger flocs. At the lowest influent temperature (10°C), both the alum and PAX suspensions had not reached maximum floe development by the end of the 10 minute initial stirring period. This indicates that flocculation takes longer at low temperatures, and this was confirmed by the results of Hanson and Cleasby (1990), who found that during laboratory experiments, there was a long lag time for flocs to develop at cold temperatures. This may help to explain some of the previous laboratory results whereby in cold temperatures, flow changes after 1h cause a disproportionately large increase in particle shedding. It could be that the filter has not ripened properly by this stage due to the suspension not flocculating fully before reaching the filter bed.

Once the suspension in the PDA 2000 was subjected to an increase in shear, all of the samples displayed a rapid break up of the flocs. Once the stirring rate was reduced to its previous rate, all of the flocs started to re-form, but in all cases, the size and rate of growth was much reduced. The alum flocs displayed more re-growth for each temperature than the corresponding PAX flocs. This result contradicts the results found by Yukselen and Gregory (2002), who observed recovery after a temporary increase in shear to follow the same patterns as the initial growth phase, i.e. PAX
temperatures. This coagulant produced small flocs in cold temperatures which are strong and recover well after being subjected to increased shear. Dyer and Manning (1999) also suggest that floc strength is not related to size, and that smaller flocs tend to be stronger because of their higher density. PAX is less affected by changes in temperature, especially when higher magnitude flow increases are applied to the filter. PAX may also be more suited to treatment plants which use a settling or clarification stage prior to filtration, to allow extra time for the settling of the flocs.

Further investigations would need to be carried out to assess how the change in temperature affects other variables such as alkalinity and conductivity. This would build a more complete picture of the chemical processes involved in floc growth and detachment during filtration. By only considering the water temperature, definite conclusions cannot be made as to the performance of the coagulants at different temperatures.

9.2.2: Vibration effects

Another variable which had a large impact on the robustness of the filter, was the effects of vibrations. This is a little researched phenomena which was observed during both laboratory and full-scale investigations. The filters suffered more breakthrough during periods of demolition and renovation, which in general reduced the efficiency of the filter. This effect may account for many of the breakthrough events that could not be related to increases in flow and it would appear that even small vibrations can cause large breakthrough events. There is currently no published literature on this phenomena which could substantiate or contradict these results and
so more research would be of great benefit in this area, especially in terms of quantifying the magnitude of the vibrations that lead to particle shedding.

9.3: Video endoscopy observations

The final technique used to assess the variation in performance of the filter at different temperatures was video endoscopy. The video enclosed (appendix 4) displays 2 filter runs using alum on a 1m mono-media bed. 50% temporary flow changes were applied after 20h. The temperatures investigated were 16°C and 25°C. It could easily be seen that at 25°C, large woolly flocs accumulated and clogged the bed. By 20h, floc detachment was occurring prior to the flow change, as seen by the migration of individual flocs. During the flow change itself, large scale detachment of the flocs was observed. However, at 16°C, far less clogging of the bed was observed, and the flocs were far smaller. Less detachment was observed during the flow change. This correlates to the jar tests which showed that alum flocs are smaller at colder temperatures. The video also relates to the laboratory results which recorded far less detachment during flow changes at colder temperatures. These results concur with the video endoscopy work performed by Ives and Fitzpatrick (1989) who recorded similar deposition patterns on the media grains, with “snow-caps” and avalanching of flocs as more deposit was added. They also found that shear forces were the dominant factor in particle detachment, and that as the bed becomes more clogged, the interstitial (pore) velocities increase due to the reduced pore volume, which subsequently causes an increase in shear. This was observed in this study by the increased clogging and detachment after 20h.
Overall the video provided good visual observations of floc behaviour within the filter, and has shown that at cold influent temperatures, alum produces smaller flocs which are distributed more evenly throughout the bed, rather than clogging the upper section of the bed. This suggests that the increased shear due to the higher viscosity at cold temperatures, may be slightly mitigated by the reduced pore clogging, and so the flocs may be more able withstand the additional force once the flow is increased.

9.4: Full-scale plant observations

Investigations were also made at full-scale plants in order to establish whether the results found at laboratory scale could be realistically used to predict real filter behaviour. Three plants were analysed, Plants X, Y and Z. In general, the results from the filters at these plants showed that (with the exception of plant Z) flow changes do cause an increase in particle breakthrough, but that the magnitude of the shedding was not dependent on the timing of the flow change. All three plants have benefited from the installation of a combined filtrate particle counter, which in all cases was able to pick up breakthrough that was missed by the turbidimeters. Roder (2002) recommended the use of particle counters in full-scale plants, but makes the point that there is no standardised level of acceptable breakthrough. Wilson and Morse (2002) also state that although particle counters are a valuable diagnostic tool, the counts cannot be used as a direct analogue for Cryptosporidium, as their research found no correlation between particle counts in the 2-5µm range and oocyst detection. However, they still provide far more sensitive information on particle breakthrough, and record breakthrough events far more quickly than turbidimeters.
Plant X illustrated that if the processes prior to filtration are optimised, i.e. the operation of the DAF plant, filter runs of much longer duration can be achieved (in this case there was no deterioration of the filter effluent after 100h). This duration far exceeds the recommendations suggested by Fitzpatrick (1998), who states that filters are normally backwashed every 24-48h. Kawamura (1991) recommended only backwashing for a short period of time, terminating when the washout water had a turbidity of 15NTU. However, this is not advisable as it could lead to mud-balling within the filter, whereby flocs left within the filter during the backwash can bind parts of the media together and create areas within the filter which increase the headloss and provide poorer filtration, due to the clogged pores. This was seen at this plant, before the backwash process was optimised.

Plant Y provided results which showed the exact reverse, whereby poor clarification prior to filtration meant that the solids loading was too great for the filters and resulted in poor performance. This plant had many particle breakthrough events that were unrelated to flow changes, and many of these were thought to be related to vibrations close to the filters, which has been previously explained. The filters recorded an increase in breakthrough during spate conditions, and the shedding spikes during flow changes were more pronounced when the raw water quality was reduced. The backwashing process was also sub-optimal at this plant, which resulted in a large amount of solids being left in the filter after washing. Cleasby and Logsdon (1999) stated that the backwashing process is the most common cause of filter failure, and that the backwash design, e.g. the position of the washout trough, is critical to ensure good subsequent performance. The filter design for backwashing was certainly a major fault at this plant, and the filters which had a washout trough to one side (filters 1-7) were unable to remove as many particles during the backwash as those with a
central trough. This was because the distance from the opposite side of the filter to the washout trough was too great for the backwash water to reach before the process stopped, and there were no surface jets to encourage the movement of the water across the filter. This resulted in a much higher initial solid loading after backwash for filters 1-7. This is an ideal example of how processes must all work together to provide satisfactory performance, and that the filtration process alone cannot maintain high quality water.

The final plant Z had excellent filter performance and as such, suffered very little breakthrough during flow changes, or at any other time during the filter runs, even during spate conditions. This was an example of optimised processes providing a very robust filtration system.

Overall, the work performed at the full-scale plants provided an excellent opportunity to relate the laboratory results to real situations, and in many cases the laboratory results largely predicted breakthrough events occurring within the full-scale filters. Examples of this were the poor performance at plant Y during both spate (increased solid loading) conditions, and during periods of vibrations, and the increased breakthrough during flow changes.

However, it must be realised that full scale operation is far more complex than complex laboratory experiments, and this was highlighted by the large amount of breakthrough spikes unrelated to any type of flow change.
This model, developed by Stevenson (1997), was used to investigate its performance against the results achieved in the laboratory. Filter runs were simulated in the model which corresponded to every variable tested in the laboratory column. The results showed that the model could be used to accurately predict the filter behaviour when flow changes were performed on a mono-media bed. The patterns of increased breakthrough with both time and magnitude were observed, and the model also displayed the benefits of introducing the flow changes gradually, in terms of limiting breakthrough.

However, the model was not as accurate when the dual media configuration was used, and it also predicted completely contradictory results to those achieved in the laboratory when temperature was varied. The model suggested superior performance in warmer water, which is likely to be due to the theoretical nature of the model, whereby the water viscosity was the only parameter that could be altered to simulate a change in temperature. This meant that the shear stress acting upon the particles in the model were reduced, thus leading to increased attachment and decreased detachment.

Overall this model is a useful tool for predicting filter behaviour, but highlights the fact that filtration is a complex process and there are more process variables than can be programmed into a simulation.
9.6: Summary

This chapter has provided a balanced discussion of the results achieved during the research, and the main findings of the experiments are listed in the next chapter. It has been proved that flow changes do cause an increase in particle breakthrough, and to a large extent, this breakthrough increases with both the magnitude and the timing of the flow change. Gradual flow changes have proved to be very successful in reducing the amount of breakthrough, and so are recommended for implementation at full-scale plants where possible. Dual media has also been shown to provide very good overall performance, which illustrates the different functions of each media type, whereby the larger pore size of the anthracite provides an increase in loading capacity for particle attachment, while the finer sand grains remove any detached and finer particles before entering the effluent.

However, this research has highlighted that the filtration process is complex, and breakthrough is just as dependent on the external variables such as water temperature, as the flow increase itself. For these laboratory conditions, alum has been found to provide superior performance to PAX, especially at low temperatures, which has been explained both in terms of the floc development and shear stresses acting upon these flocs. This is a surprising result, which contradicts previous evidence of filter performance using alum, although as previously mentioned, further research to investigate other chemical parameters would be required before confidence can be given to these results.

The effects of vibrations has also provided an interesting result which needs further investigation, as this may have serious implications for the timing of construction work at treatment plants.
Overall this research has provided an in-depth investigation of filter behaviour. It is clear that care must be taken when designing and operating a WTW, to ensure that the filter design and configuration is able to cope with the solid loading, and that flow changes are implemented in a way and at times during the filter cycle which cause the least additional breakthrough into the effluent.
10 CONCLUSIONS

The aim of this project was to assess the effects of flow changes on filter performance and this has been achieved through both laboratory and full-scale investigations, as well as computer simulation work. Originally it was thought that a set of operational parameters could be produced that would give safe ranges of flow change introductions for a selection of media configurations. This could limit or reduce particulate breakthrough at individual plants during backwashing.

The basic variables tested were the magnitude and timing of the flow changes, i.e. 25-100% flow increases applied after 1-22h into the cycle. The flow changes were either temporary, permanent or gradual to simulate either backwashing or demand increases at full-scale plants. Also investigated were a range of internal and external variables such as varying influent suspension, media configuration and influent water temperature.

The results showed that the filtration process is a complex operation, and that straightforward parameters for introducing flow changes could not be drawn. It could be seen that the external variables such as water temperature and nearby vibrations had just as much influence as the flow changes applied in determining the amount of particle breakthrough during a filter run. Having assessed all of the results, the conclusions that can be drawn from this study are as follows:

- High concentration influent suspensions cause more breakthrough during flow changes at both laboratory and full-scale, mainly due to increased clogging.
• In general, the higher the magnitude of flow change applied, the greater the particle breakthrough observed.

• Only certain filter configurations suggested flow changes later in the filter run cause a higher amount of shedding. Floc compaction and biofilm growth may be responsible for limiting breakthrough during some late flow increases. Full scales studies did not display any evidence of an increase in breakthrough with the timing of the flow change, and these are more likely to have biofilms developing in the influent water.

• Gradually introduced flow changes (5% per minute) reduce the amount of shedding during flow changes when using a 1m sand and dual media bed.

• Permanent flow changes do not automatically cause a larger amount of total breakthrough than temporary flow changes, this was only observed with high magnitude increases. This suggests a small increase in water demand may not be detrimental to full-scale filter performance.

• Reduced bed depth (0.6m) experiments were not as successful, with end-of-run breakthrough observed earlier than when using a 1m bed. At cold temperatures flocs may pass straight through the filter before forming properly, thus reducing the opportunity for capture.
- Dual media beds provide excellent filtration at 5m/h, with virtually no end-of-run breakthrough for any variable tested. However, high starting flow rates could not be successfully tested in the laboratory column, and the filter could only maintain satisfactory flow rates and filtrate quality for approximately 12h.

- PAX coagulant is not as effective as alum (only for these laboratory conditions), with shorter runs and higher particle base counts being recorded. However, using this coagulant caused the filter to cope better with the flow changes themselves, and less shedding was observed.

- The temperature of the influent suspension is of great importance and this can either reduce or enhance the amount of breakthrough during a flow change. The laboratory results suggest alum performs better than PAX at cold temperatures, and alum at cold temperatures outperforms both alum and PAX at higher temperatures. Alkalinity and conductivity analysis would help explain these results further.

- Cold influent runs take longer to ripen, which has implications for flow changes performed early in the run. The suspension is likely not to have flocculated properly before reaching the media bed when no clarification stage is used.

- Vibrations are a very important consideration and these increase breakthrough in both laboratory and full-scale filters. Further work to quantify vibration effects would be of great benefit.
• Shear stress calculations indicate that flocs must be over 20% stronger to withstand the same flow changes at cold temperatures (15°C) than in warmer water (25°C).

• Filterflex model is a valuable tool for predicting filter behaviour during flow changes. However, this was only true of mono-media beds, and also predicted effects of temperature were the reverse of what was observed in the laboratory.

Overall, this has been a successful, in-depth study of filter behaviour for a range of process variables, and has provided some useful results that can be of direct importance to full-scale treatment plants. Recommendations for plants are that care should be taken when introducing flow changes, and wherever possible these should be done gradually, as this has been proved to limit the additional shedding. During winter months, backwashing should be staggered so that it does not coincide with the first hour of another filter start up, as ripening takes longer and leaves the filter more vulnerable to breakthrough during flow changes.

Plants should have the ability to change the dosing rapidly during spate conditions, as sub-optimal dosing is one of the main factors in reducing the filter performance and increasing the breakthrough effects during flow changes.

When combined together, the laboratory, full-scale and computer modelling results give a comprehensive idea of the amount of breakthrough that is likely to occur during a flow change, for a wide range of filter conditions. This breakthrough is a
complex process and both internal and external variables must be considered together to provide an accurate prediction of breakthrough.

10.1: Further research

As with any study of such duration, several areas of investigation have been discovered that would aid in providing a more complete understanding of filter behaviour. Time constraints have meant that these could not be studied in depth but would benefit from further research. These include:

- Introducing flow changes between 7-18h into the filter cycle to investigate the floc compaction and possible biofilm growth. This could be done in conjunction with video endoscopy to visualise these flocs.

- Revisit the full-scale plants during the winter to establish the effects of influent temperature on a larger scale.

- Experiments could be repeated using both a different configuration of the dual media, and also GAC, as many treatment plants use a different media arrangement to those tested in the laboratory.

- Different types of coagulant could be used, for example ferric and polyelectrolyte chemicals, specifically to test the effects of temperature on these coagulants.
- Putting a clarification stage into the laboratory apparatus, to investigate the subsequent performance of PAX at a range of temperatures, as it appeared in these experiments to be slightly unsuitable for direct filtration.

- Investigation into chemical parameters of the flocculated suspension at different temperatures to provide a more comprehensive understanding of alum and PAX performance.

These would all provide useful information and may lead eventually to the production of working parameters and guidance on safe practices at full-scale plants, to reduce particle breakthrough and thus limit the potential for *Cryptosporidium* outbreaks.
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Appendix 1:

IWA poster presentation

Paris 2000
INTRODUCTION
- Filtration is vital for effective drinking water treatment
- Several types of media can be used, e.g. sand and GAC
- Rapid filters remove floculated particles, which are usually about 2-15μm in size
- Filters become more efficient after about 30 minutes. This is called the "Ripening" period
- Filters must be backwashed every 24-48 hours.

PROBLEMS IN FILTRATION
- Particles and pathogens eventually pass through the filter and into the water supply
- Cryptosporidium is resistant to chlorination and so must be removed during the filtration stage.
- Flow rate changes during filtration can cause increased particle breakthrough. This is a problem as most filters experience increases when other filters are backwashed.

INVESTIGATING THE PROBLEM
- This research is based on a laboratory filter. (See centre photo)
- The initial flow rate is 5-20m³/h
- The filter runs are 8 hours in duration
- Flow rates are increased after 1 hour of the filter run to examine the effects of flow rate increases on particle breakthrough
- The change varies in magnitude, with increases of 25, 75, 100 and 150%
- Influent water contains 50mg/l Kaolin suspension and 0.15mg/l Alum coagulant

RESULTS TO DATE
- Particle counts are measured, as they give an accurate record of breakthrough
- The particle counter records particles in the Cryptosporidium size range, 2-5μm and also sizes up to >15μm, which may be flocs containing smaller Cryptosporidium sized particles
- Particle counts and flow rates are monitored continuously
- Turbidity, headloss and pH are also recorded at regular intervals

ANALYSIS AND DISCUSSION
The graphs show particle counts during the filter run, with the corresponding flow rates. When the flow changes, although there is some breakthrough, it is not very significant this early in the run. The higher the flow increase, the more sustained the particle breakthrough. This is illustrated by a narrow spike during the 25% flow increase but a far wider spike with an increase of 150%. Such a large flow increase is unlikely to occur at a plant but is useful to illustrate this trend. All graphs show several spikes which are unrelated to the flow increases and may be due to disturbance of the rig. The headloss curves are very similar, with higher flow increases causing higher headloss readings. However, after the flow change, readings return to comparable values, as limited shedding means that there is little reduction in headloss.

FURTHER WORK
- The duration and time of the flow change will be investigated
- Video endoscopy will show actual particle detachment
- Various bed depths and media types will be examined
- Comparisons will be made to pilot plant data
AWWA WOTC Oral presentation

Salt Lake City, USA

November 2000
THE EFFECTS OF FILTRATION RATE FLUCTUATIONS ON CRYPTOSPORIDUM Sized PARTICLE BREAKTHROUGH

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ABSTRACT

Filtration is an essential process in drinking water treatment. Recent Cryptosporidium outbreaks have highlighted concerns about filter efficiency and in particular particle breakthrough. Breakthrough has been linked to the ripening stage, when up to 90% of the entire breakthrough occurs, due to poor removal (Amirtharajah, 1988), and also during flow rate changes. This research aims to expand upon this knowledge, specifically when flow rate changes occur. Laboratory experiments were conducted on a single filter column which had a starting flow rate of 5m/h. Various flow increases were introduced instantaneously at different points during the filter run and each flow change was 30 minutes in duration, after which the flow was returned to the starting value. The results show that flow rate changes cause an increase in particle breakthrough, which is more pronounced with flow changes later on in the runs and with higher magnitude of flow rate increase.

KEYWORDS

Filtration, Cryptosporidium, flow rate changes, particle counts.

INTRODUCTION

Particulate breakthrough has long been recognised as a problem in drinking water filtration, and researchers as early as Cleasby et al. (1963) have suggested that altering the flow rate during a filter run was not recommended. Research has shown that Cryptosporidium sized particles,(i.e. 3-5μm in diameter) are least likely to be removed during filtration. However, this particular pathogen is resistant to standard chlorination and causes intestinal illness in humans if ingested through the water supply. For this reason it is vital that the oocysts are removed during the filtration stage. Traditionally particle breakthrough has been monitored using turbidimeters, however these readings can be misleading as they do not give an accurate measure of the concentration of individual particle size ranges. This means that the risk of a Cryptosporidium outbreak cannot be assessed. Particle counters are a better tool for such research as confirmed by Hall and Croll (1997), who concluded they were far more sensitive for measuring effluent quality, and Fitzpatrick et al. (1999) who monitored particle breakthrough at plants in the UK and USA and found that increases in particle counts corresponded to increases in flow rates.
Work is beginning to focus on minimising particle breakthrough in light of the *Cryptosporidium* risk, for example Emelko *et al.* (1999) examined coagulation conditions and the amount of subsequent particle shedding. Start up strategies and backwashing techniques have also been researched by Koudjonou *et al.* (1999) with regard to minimising particle breakthrough. Both of these investigations have suggested that flow rate changes may have some effect on breakthrough but have not examined it fully. The results of this research are important because most filters experience a certain amount of flow rate increase when one filter is taken offline for backwashing, and smaller plants with fewer filters may experience proportionally higher changes. The UKWIR report (1995) suggested flow changes should be made at a maximum rate of 5%, and 1.5% for waters producing a weak floc. This needs further investigation.

**EXPERIMENTAL METHODOLOGY**

![Experimental Methodology Diagram](image)
Fig. 1 shows the laboratory filter column, 2m in height and 166mm internal diameter which contained 1m depth of Leighton Buzzard sand, size 0.5-1.0mm. The filter was operated at an initial flow rate of 5 m/h, which corresponded to 1.8 litres/min for the column. The influent water was London tap water and contained 50mg/l Kaolin light suspension and 0.25mg/l as Al. of aluminium sulphate (jar tests were performed to determine the optimum alum concentration). The coagulant was added to the water directly before entering the column itself, to prevent re-circulating of the coagulant into the main tank, via the constant head overflow. The kaolin suspension provided an influent turbidity of approximately 50 NTU. This was an unnaturally high solid load for direct filtration but was used to obtain rapid clogging. This would simulate in one day the effects of a flow changes during a 24/48 hour filter run, as the bed would contain similar amounts of solids.

The filter runs were 8 hours in duration (with the exception of the runs with 7hr flow change, which were 9hrs). The filter was operated with a constant head so the flow rate declined gradually during the runs.

Both the particle counts and the flow rate were monitored continuously using a MetOne particle counter, model WGS 267, and a MagMaster flowmeter respectively. These are labelled in Fig. 1.1. Headloss from water manometers, pH, turbidity and temperature were also recorded at regular intervals. The particle counter measures particles in several size ranges, from 2 to >15 μm but for the purposes of this paper, only the 2-5μm and >5μm ranges are discussed, as these represent both Cryptosporidium size range and also larger flocs which may contain the pathogens.

The flow was increased by 25, 50, 75 and 100% of the initial flow rate and this change was instigated instantly for 30 minutes. After this time, the flow was instantly returned to the starting flow rate for the remainder of the run. Each flow change was performed after 1, 4 and 7 hours to examine the effect of particle shedding and any reduction in particle removal. During the flow changes, both the kaolin and alum dosing rates were increased in proportion to the flow increase, so as to maintain the same amount of solid and coagulant dosing for the higher flow. This was achieved by increasing the speed of the peristaltic pump operation so that, for example, with a 100% flow increase, the filter was still supplied with 0.25mg/l alum rather than 0.125mg/l.

After each run the column was backwashed using a set procedure of 5 minutes water wash, at 20% bed expansion followed by 5 minutes of collapse-pulsing air and water wash (Amirtharajah, 1993), and then a further 5 minutes of water only backwash.

The experimental results were compared to those of a mathematical model written by Stevenson (1997). The exact flow changes performed in the experiments were programmed into the model, although the water chemistry parameters were kept to the original values set by Stevenson, for example the nominal floc size was set at 5 microns and the feed floc concentration 0.002%v/v, which was a volume concentration in the influent.
RESULTS AND DISCUSSION

The results are grouped according to the time of the flow rate change, rather than the percentage flow increase, as comparisons between the graphs can be made more easily. For all runs, the temperature of the water ranged from 20-24°C and the pH was on average 6.5. The table below shows the particle counts/ml of London tap water. This was required to give the background levels and was useful for filter efficiency comparisons.

<table>
<thead>
<tr>
<th>PARTICLE SIZE (µm)</th>
<th>TAP WATER COUNTS PER ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3</td>
<td>46</td>
</tr>
<tr>
<td>2-5</td>
<td>100</td>
</tr>
<tr>
<td>3-5</td>
<td>54</td>
</tr>
<tr>
<td>5-7</td>
<td>8</td>
</tr>
<tr>
<td>7-10</td>
<td>8</td>
</tr>
<tr>
<td>10-15</td>
<td>5</td>
</tr>
<tr>
<td>&gt;15</td>
<td>23</td>
</tr>
<tr>
<td>&gt;5</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 1: particle counts in London tap water
Fig. 2: Particle breakthrough with flow increases after 1 hour into the filter run

(A) 25% flow increase

(B) 75% flow increase

(C) 100% flow increase

(D) 150% flow increase

1 l/min = 0.36 m/h
Control Runs

Although not illustrated here, three control runs were performed to assess the performance of the filter without any flow rate changes. The results showed that the particle breakthrough for all size ranges, after a ripening period of approximately 40 minutes, was minimal and did not exceed background levels, i.e. those particle numbers in tap water. There was no reduction in efficiency after 8 hours and the filter was removing all but the background level of particles. The flow rate dropped by an average of 0.2 l/min throughout the 8 hour period.

1 Hour flow rate change

Figure 2 shows the amount of particle breakthrough with a flow rate change after 1 hour. It is apparent from these four graphs that breakthrough is related to flow changes as both particle size ranges show an increase in counts per ml when the flow rate is increased. It can be seen that the particle breakthrough remains low throughout the entire runs, with a maximum peak of 350 counts/ml during the 150% flow rate change. However, this is not very significant, especially when compared to the values of later flow rate changes. The filter has a consistent efficiency towards the end of the runs, which suggests that a flow rate change this early in the run has no long term effect on the filter performance. There are several small spikes on all of the graphs which are unrelated to the flow rate change. These are probably due to disturbance of the apparatus, for example knocking of the support frame which has led to increased breakthrough. These are highlighted more on these graphs due to the smaller scale for the particle counts but do occur on every graph. Unlike the 4 and 7 hour flow rate changes, the 1 hour flow change increases to a maximum of 150%. Such a large flow change is unlikely to occur at a plant but was useful in this study to examine the effects of such a huge increase.

4 hour flow rate change

Figure 3 shows a much more pronounced effect of the flow rate increases. Although the 25% flow increase shows little breakthrough during the increase, the larger flow rate changes show not only an increase in particle counts during the change, but also a reduction in filter efficiency towards the end of the run. This is more pronounced with the 100% increase, graph (D). It can also be seen that the higher flow rate increases, graphs (C) and (D), produce a breakthrough spike larger than that occurring during the ripening period. These two graphs show a more sustained particle breakthrough during the flow rate change. This again is most noticeable with the 100% increase, which has a high initial peak and then the amount of breakthrough gradually increases during the last 15 minutes of the flow change to form a secondary peak. It is clear that the run depicted in graph (D) starts to fail almost immediately after the flow returns to the original rate, and the breakthrough rate rapidly increases to the end of the run. Although this occurs with a 50 and 75% increase, the effect is not as rapid or dramatic. With the number of particles retained within the bed by this stage, it suggests that such a high flow rate increase could be catastrophic at a full scale plant.
Fig. 3: Particle breakthrough with flow increases after 4 hours into the filter run

(A)

(B)

(C)

(D)
Fig.4: Particle breakthrough with flow increases after 7 hours into the filter run

(A) 25% flow increase

(B) 50% flow increase

(C) 75% flow increase

(D) 100% flow increase
7 hour flow rate change

This set of results, (fig. 4), shows the greatest amount of particle breakthrough during the flow rate changes. Again, as with the changes after 4 hours, the 25% increase shows the least amount of breakthrough. However, graphs (B), (C) and (D) all follow a very similar pattern of breakthrough, which matches that of Fig. 3 (D), i.e. a huge initial peak at the start of the flow rate change, followed by an increase to a secondary peak, and finally an immediate failing of the filter once the flow was decreased to the initial rate. All three graphs display peaks far larger than the ripening peak, when the flow increase occurs. Surprisingly, the maximum peak of the 100% flow increase, graph (D), is only half of that of the 50% flow increase. This may be due to the sampling period of the particle counter, which sampled for 30 second every 2 minutes. This means that if the maximum breakthrough fell outside of the sampling time, it may not have been recorded and thus altering the overall record of breakthrough.

Headloss graphs

Figures 5-7 illustrate the headloss measured across the bed during each filter run. They are grouped according to the time of the flow rate change which allows a clear pattern to be seen. For each graph it can be seen that the headloss gradients are very similar for each filter run, especially for flow rate changes after 1 hour. The graphs show that higher flow rate changes cause a drop in the headloss immediately after the flow has returned to the initial rate. This is expected as the flow increase detaches particles from the bed and so reduces the clogging. This is illustrated most effectively in Fig. 7, where the 50% flow increase graph is reduced to the same value as that of 5 1/2 hours into the run, i.e. the flow change has removed that last 1 1/2 hour of particle clogging. Conversely, the 25% increase graphs show no drop at all, as very little breakthrough or detachment occurred. Fig.7 also displays an increase in the headloss gradient of each run after the flow rate change. This was not expected as it does not correspond with the increased breakthrough illustrated on fig. 4, which would indicate a slowing headloss increase. There are differences in the starting headloss for all graphs, this is probably due to variation in the water temperature and also bed compaction after backwashing.

Multiple Flexible layer (Mflx) model graphs

To a certain extent, the Mflx graphs resulting from Stevenson's model, Fig. 8 and 9, correspond very well to the actual experimental runs. The graphs show both increased particle breakthrough during the flow rate change, and also unrelated increases which are function of the model. The Mflx program was run for all of the variables, although only the 25% and 100% increases are illustrated in this paper. However, it is apparent that the model confirms the importance of time in the filter run, as Fig. 8 (C) shows far more breakthrough than (A), despite both having the same flow rate change. Another interesting point to note is that Fig. 9 (B) and (C) both display greater particle breakthrough during the flow change than during the ripening period, which matches the experimental findings. Unlike the filter runs, the Mflx graphs show no sign of diminishing efficiency towards the end of the run for any of the variables tested. We are seeking to understand exactly what is happening when this occurs. Also, the model graphs only display one peak during the flow rate change, whereas the experiments had a secondary peak towards the end of the flow increase.
Figs 5–7: The effect of flow changes on headloss development
Mflx computer simulations of the breakthrough corresponding to 25% and 100% flow rate increases

![Images of graphs showing breakthrough simulations for 25% and 100% flow rate increases at different time intervals.](A) (B) (C)

Although this program is useful in predicting the overall pattern of breakthrough, it is not straightforward to directly compare the model and practical experiments. It is difficult to correlate counts/ml with residual concentration when it is expressed as a volume concentration.
DISCUSSION

It has been shown in these experiments that under normal operating conditions, i.e. before the flow rate changes, the filter operates very well indeed, and removes all of the kaolin particles in the water. In many cases, the counts/ml are even less than the background counts of London tap water.

The timing of the flow rate change is critical, flow increases after 1 hour do not have a large or long lasting effect on the overall operation of the filter whereas increases after 7 hours cause severe problems in terms of particle breakthrough and subsequent filter efficiency. This is due to the fact that high flow increases detach particles from the bed, some of which come straight out into the effluent, and some get re-attached deeper in the bed, which are removed later in the run. The later the flow change, the more solids are already contained in the bed and so there is more to detach at deeper levels which increases the chance of the particles passing straight out of the filter. This may also account for the failing of the filter later in the run, as those particles which had been re-attached deep in the bed are increasingly detached.

It appears that a 25% flow increase is close to the lower limit for particle breakthrough for these experimental conditions, as none of the runs with this rate change experienced a significant amount of breakthrough, even after 7 hours. The efficiency of the runs were also not impaired. Further investigation is required to examine exactly what the lower limit is for certain media and suspension conditions.

Although not directly investigated in this study, the importance of optimum coagulant dosing was highlighted during one filter run. The supply of Alum was disrupted and this led to an immediate decrease in filter efficiency, with particle counts reaching 2000 counts/ml. Once the coagulant dosing was restored, the particle breakthrough rapidly reduced.

Finally, although breakthrough was measured using a particle counter for this study, turbidity readings were also taken at 30 minute intervals. The results from these readings were very inconsistent, and not very sensitive to breakthrough. For example particle counts between 5 and 150 /ml resulted in identical turbidity readings of 0.19NTU, and for a breakthrough peak of over 11000 counts/ml, the turbidimeter recorded a reading of 2.3NTU.

CONCLUSIONS

- This study has confirmed that flow rate changes should be avoided during filtration and that the later in the run the change occurs, the higher the amount of breakthrough.
- The results have shown that although higher flow rate changes cause increased breakthrough, by far the more critical parameter is the time of the increase. A 50% flow increase after 7 hours can cause more breakthrough than a 100% increase after 4 hours.
• Flow changes of less than 25% may not cause much breakthrough under these conditions, nor are the effects long lasting, but they still have the potential for passing Cryptosporidium sized particles into the supply and so are inadvisable.
• Coagulation is vital for successful filtration and dosing rates must be altered to correspond with any flow changes, for example during the backwashing of other filters.
• Particle counters are more effective for monitoring particle breakthrough and in particular assessing the risk of a Cryptosporidium outbreak.
• The mathematical model, Mflx, is a good indicator of breakthrough during flow changes and displays the same general pattern as the experimental results.

Overall, the recommendations arising from this study are to keep flow rate changes to a minimum, and those that are unavoidable, such as backwashing at plants with no storage facility for backwash water, should be done as early into the run for the remaining filters as possible.

FUTURE WORK

Further studies will be carried out to examine the effects of longer and multiple flow rate changes with regard to breakthrough. Also, why the later flow rate changes cause a decrease in the filter run time. Investigations will also study the amount breakthrough caused by flow rate increases on a shallower filter bed, and also that of different filter media. Finally floc strength will be varied and subsequent breakthrough examined.

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REFERENCES


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Oral Presentation
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PARTICLE BREAKTHROUGH CAUSED BY FLOW RATE CHANGES DURING RAPID GRAVITY FILTRATION

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ABSTRACT

Particle breakthrough has long been identified as a problem in filtration and there have been many studies which have examined the point during the filter run where most breakthrough occurs, for example the ripening period. Understanding the causes of breakthrough has become more important in light of recent Cryptosporidium outbreaks, most notably in the USA and UK, as the parasite cannot be destroyed during the disinfection stage.

Laboratory experiments have been conducted on 0.5-1mm sand and flow increases of between 25-150% have been introduced at varying times during the filter run, above the starting flow rate of 5m/h. Various influent concentrations have been used and the filter performance assessed. Results show that later flow changes cause a higher magnitude of breakthrough and that the influent suspension plays an important part in the overall performance.

KEYWORDS

Filtration, flow rate changes, particle counters

INTRODUCTION

Filtration is a vital process for the treatment of drinking water. Several reports have stated that flow rate changes during the filter run may increase breakthrough, one of the earliest being in 1963¹. The importance of this is that a bank of filters experiences a degree of flow fluctuation as one filter is backwashed. The degree of change depends on the number of filters in operation, the fewer the number of filters, the higher the proportional flow change. More recent works have focused in more detail on minimising particle breakthrough, for example optimising coagulation conditions² and start up and backwashing strategies³. The aim of this current research is to determine what type of flow rate change causes most breakthrough and at what stage during the filter run the flow change is most harmful in terms of particle shedding.

In the past, most research has relied on turbidity and headloss measurements as indicators of particle breakthrough. This is likely to give misleading results however, as individual particle size concentrations are not measured. A particle counter is more suitable for this task as it can measure several size ranges of particles, including those in the Cryptosporidium size range, i.e. 2-5μm.
METHODOLOGY

The laboratory filter used was 2m in height and 166mm internal diameter, and contained a 1m bed of 0.5-1mm sand. The filter was operated in declining rate mode and the starting flow rate was 5m/h, which meant 1.8 l/min through the column. The influent suspension contained 50mg/l of kaolin (47NTU), which was then reduced to 10 mg/l (9NTU) for the second set of experiments. Alum was dosed directly into the top of the column via a baffle mechanism. This was to flocculate sufficiently the suspension in the absence of sedimentation tanks and rapid mixers. The runs were either of 8 or 24 hours duration, depending on the timing of the flow change. The flow changes themselves were introduced instantly after 1, 4, 7, 18 and 22 hours, although only 1 flow change was applied to each filter run. The flow change was of 30 minutes duration, after which time the flow was returned to the starting value of 5m/h. The magnitude of the flow changes ranged from 25 – 150%.

The flow was monitored continuously using an electromagnetic flow meter and particle counts were taken using a Met One particle counter. This had the capability to record 6 separate size channels from 2->15 microns. Temperature, pH, turbidity and headloss measurements were also recorded. After each run, the bed was backwashed using a set procedure of 5 minutes water wash at 20% bed expansion, followed by 5 minutes of water and air scour to produce collapse pulsing conditions. This was finished of by 5 minutes of water only wash to remove any trapped air. Due to time constraints, only 1 filter run was performed for each variable.

RESULTS

The following graphs are grouped according to the influent suspension used and also the % flow increase applied. Although several size ranges have been recorded during this study, this paper only presents those in the 2-5μm and >15μm size range as these represent the Cryptosporidium size range and also larger flocs which may contain the pathogens.

Preliminary Experiments

Before carrying out the filter runs, the size distribution of particles in both London tap water and the influent suspensions was obtained. This provided the background count levels for the experiments and also enabled removal efficiencies to be calculated. The temperature of the water ranged from 20-24°C and the average pH was 6.5.

Although not displayed graphically, control runs were performed without flow changes for both influent suspensions. These showed that the ripening period was about 40 minutes for each suspension, and that once in steady state conditions, the particle counts were at background levels, i.e. those already found in London tap water. In both cases the flow dropped by approximately 0.2 l/min during the 8h and 24h period. There was also no reduction in efficiency towards the end of the runs, suggesting that the run time could have been increased without a reduction in water quality.
Fig. 1-25% Flow increases at various times during the filter run.

Graphs show flow rates and particle counts per milliliter over different time periods (1, 4, and 7 hours). The graphs indicate changes in particle counts with varying flow rates.
Fig. 2 100% Flow increases at various times during the filter run. 50 mg/l kaolin.
DISCUSSION

Figure 1 illustrates the effects of a 25% flow increase after 1, 4 and 7 hours using a concentration of 50mg/l. It can be seen that this magnitude of flow increase does not cause a substantial amount of breakthrough for our filter conditions. The maximum peak is 250 counts /ml during the first 5 minutes of the flow increase after 7 hours. It also shows that for all three runs, the Cryptosporidium sized particles were shed in larger numbers than those above 5 microns. The recovery of the filter is very good after the flow change and there was no reduction in filter efficiency towards the end of the filter run. Further work must be done to investigate whether a 25% flow increase causes minimal breakthrough for all filter conditions and also what is the maximum flow increase that can be permitted before additional breakthrough occurs for these conditions.

Figure 2 shows the results of a 100% flow increase. The graphs display far more breakthrough during the flow changes and unlike the 25% increases, the breakthrough actually remains at a raised level for the entire duration of the flow change. They also show a secondary spike which is reached during the flow change itself. The 4 hour flow change also resulted in a higher shedding of the larger particles, i.e. those above 5μm. Both the 4 and 7 hour flow changes result in the rapid increase of Cryptosporidium sized particles in the effluent, and also a less dramatic rise in the larger particle counts. The maximum breakthrough peak of the 7 hour flow increase is actually half that of the 4 hour graph. This is thought to be due to the counting period of the particle counter. It was set to count for 30 seconds every 2 minutes. This means that if the maximum peak fell outside of the counting sequence, it would not have been recorded and led to anomalous results.

When combined, these two sets of graphs give a clear pattern of particle breakthrough trends during flow changes. Firstly it can be seen that the higher the magnitude of flow change, the higher the amount of particle breakthrough will be. More importantly though, they illustrate the importance of the timing of the flow change, as the same flow magnitude causes more breakthrough after 7 hours than after 1 hour. This is important as it could determine when a filter should be taken offline for backwashing, so as to minimise the disturbance to the remaining filters in the series. The reason for this is that there is more sediment in the bed after 7 hours and at deeper levels. When a flow change occurs, some of the sediment is removed straight into the effluent and some is transported deep into the bed, which is then removed during the remainder of the flow change and also at later stages of the filter run. This can account for both the secondary spike on the breakthrough graphs and also possibly for the early failure of the filter during the later flow changes.

Obviously, the combination of a large flow increase late on in the filter cycle could be catastrophic in terms of particle breakthrough and the subsequent performance of the filter after the flow change.
Figure 3 illustrates the second set of experiments using the lower influent concentration of 10 mg/l. Flow changes after 1, 4, 7, 18 and 22 hours are shown and for the later flow changes, the runs were increased in duration to 24 hours. These graphs do not show a distinct pattern that was observed in the 50 mg/l concentration experiments. The amount of breakthrough does not always increase with time, it can be seen that a 22 hour increase causes the same amount of breakthrough as the 1 hour change.
Figure 4 is similar to figure 3, except that the flow increase is 100%. Again, these graphs show some anomalous results, with no correlation between particle counts and the time of the flow change. The 100% graphs do show a slightly longer period of increased breakthrough during the flow changes, which was expected given the results during the flow changes of the 50 mg/l experiments.
Headloss across the bed, 4 hr flow increase using S O m/g/l kaolin

Headloss across the bed, 4h flow increase using 10mg/l kaolin

(a)

(b)

Fig. 5 Comparisons in headloss across the bed with flow changes after 4 hours. (a): 50 mg/l, (b): 10 mg/l

Headloss

These two graphs illustrate the headloss development during a 4 hour flow change, for all flow magnitudes and influent concentrations. Figure 5 (a) shows the linear nature of headloss development and also correlates well with the flow graphs. The 25% flow increase does not cause much disturbance in headloss whereas the 100% increase actually causes a decrease in the headloss after the flow change due to the removal and redistribution of sediment within the media. Figure 5(b) shows a slower rate of headloss development which is expected due to the lower influent concentration. Although the 25 and 75% lines follow a similar development trend outside of the flow change, the 100% graph displays a far slower rate of increase, which cannot be explained as the particle count graph displays no irregularities.
Overall, figures 4 and 5 show far less breakthrough during the flow changes and a less defined pattern than those of the 50 mg/l graphs. The flow changes result in a far narrower breakthrough spike and in general there is no evidence of the secondary spikes which were so obvious with the higher influent concentration. Although the 75% increase after 7 hours displays 2 peaks during the flow change, the counts in-between are at background levels and so it is more likely to be due to the actual turning of the gate valve to alter the flow. Therefore this secondary spike is not of the same nature as those displayed in the higher concentration graphs. With the exception of the 100% flow increase after 7 hours (which also displayed the only secondary spike), none of the filter runs showed any significant reduction in removal efficiency after the flow change. This is another contrast to the 50 mg/l concentration experiments as many of the filter runs failed immediately after the flow change. The final difference between the two sets of graphs is that for the lower concentration experiments, the 100% flow increase did not automatically produce a higher amount of particle breakthrough than the 75% increase. There are several possibilities for this, one being that the sediment form stable deposits within the bed and so are harder to remove. Work must be done to investigate whether there is a certain time during the run when the stability occurs. Flow rate changes between 7 and 18 hours will be required to ascertain this. The lack of breakthrough with time may also be a combination of greater attachment forces during the run or compaction of the particles within the bed. This would increase the density and reduce the size of the sediment and thus reduce the removal potential. Another possibility is the development of biofilms which may encompass particles or encourage the attachment of others. The use of video endoscopy will enable attachment/detachment processes within the bed to be examined and so may provide a better understanding of what happens during the later flow changes.

In general, the filter performed very well and outside of the flow changes, the particle counts were at, and sometimes below, the background counts for London tap water. This applied for both influent suspensions. Although the 50 mg/l experiments show a very clear pattern of increased breakthrough with time and magnitude (as detailed earlier), when comparing the entire data set fewer conclusions can be drawn. This highlights the problems in laboratory research as the reproducibility of the filter runs is limited and so care must be taken when interpreting results from individual filter runs.

However, the results show unquestionably that flow changes do cause an increase in particle breakthrough and that the influent suspension is an important factor in the overall performance of the filter.

CONCLUSIONS

1. The main conclusion that can be drawn from this study is that flow changes do cause an increase in particle breakthrough, and should be avoided if possible during filtration, especially later in the filter cycle.
2. The concentration of the influent suspension is an important factor in affecting the filtrate quality during flow changes. The higher turbidity experiments resulted in much greater particle breakthrough during flow changes.
3. Lower influent concentrations tend to recover better after flow changes and do not reduce in efficiency at the end of the runs. This may lead to the potential for increased run time before water quality is reduced.
4. Laboratory experiments are not easily reproduced and so unambiguous conclusions cannot readily be drawn from one set of data.

5. In all cases for our filter conditions, a 25% flow increase results in minimal particle breakthrough and further investigation is required to test if this is true for other filter conditions. However, they still have the potential for passing Cryptosporidium into the supply.

ACKNOWLEDGEMENTS

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Understanding The Effects Of Flow Rate Changes On Particle Breakthrough During Filtration

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ABSTRACT

Water quality during filtration can be affected by many factors, and this research evaluates the effects flow changes have on the filter, in terms of additional breakthrough. The paper also looks at the external factors which may affect this shedding, at both laboratory and full scale. Flow changes of differing magnitudes and at various times during the filter cycle were applied, and effluent particle counts were monitored. Results show that whereas flow changes do cause an increase in particle breakthrough, the degree is more likely to be related to external factors such as water temperature, vibrations and coagulation efficiency.

KEY WORDS

Filtration, Flow changes, Cryptosporidium

INTRODUCTION

The importance of minimising particle breakthrough during filtration is widely acknowledged and many reports have suggested that both the ripening period and flow changes result in higher levels of breakthrough than steady state conditions. This latter cause is important, as it is largely unavoidable in treatment plants as a filter backwash causes a flow increase in the remaining filters. These problems are further highlighted by recent outbreaks of cryptosporidiosis in the UK and USA. As the Cryptosporidium oocyst is resistant to most economic forms of disinfection, good filtration is vital.

The aim of this research is to investigate which types of flow change are most harmful in terms of breakthrough, what external conditions affect this breakthrough, and finally why the shedding occurs under these conditions. Investigations have been made in three ways; laboratory, full-scale experiments, and computer modelling.

The laboratory work was carried out on a 2m column comprising a 0.6-1m bed of sand. Flow increases of between 25-100% were made on a starting flow rate of 5m/h. The increases were of varying duration and were applied between 1 and 22 hours into the filter runs. The effects of influent suspension were examined by repeating each experiment using 10 and 50 mg/l kaolin. Both effluent particle counts and flow rates were constantly recorded, and temperature, turbidity and headloss were also monitored.

All of the laboratory variables have been programmed into the Filterflex model (Stevenson, 1997) to compare actual and theoretical results. Observations have also been made at full-scale plants in the UK to assess whether laboratory research is applicable to full-scale performance.
RESULTS

For graphical simplicity, the breakthrough results have been grouped into two size ranges, 2-5μm and >5μm. This represents both the Cryptosporidium size range, and also larger flocs which could contain pathogens. Most graphs display only the 2-5μm range.

![Particle breakthrough with a 100% flow increase at varying times](image)

**Figure 1: Temporary flow changes using 50mg/L kaolin**

This first graph shows 100% temporary flow increases applied after 1, 4 and 7 hours. The duration of the flow change was 30 minutes, so as to simulate a filter going offline for backwashing. The influent suspension of kaolin was very high so as to speed up the solid loading and thus simulate end of run breakthrough much earlier. A very distinct pattern of breakthrough emerged whereby flow changes later in the filter cycle caused more breakthrough, as did higher magnitude increases. Also of interest was the occurrence of a "secondary peak" during the actual flow change, and an almost immediate failing of the filter after the flow had been returned to its original value. The peak is thought to be due to the initial increase in shear stress caused by the flow change. This dislodged many particles straight through the filter, and also transported some sediment to the lower reaches of the bed, which were increasingly removed under the higher flow, hence the 2<sup>nd</sup> peak.

The secondary peak required further investigation, and so the flow changes were made permanent (thus simulating a filter taken out of service). Gradual flow changes were also introduced, to investigate the 5% per minute recommendations for flow changes. These experiments were performed using both 50mg/L and a more realistic 10mg/L kaolin suspension.
Disappointingly, these results did not show any conclusive patterns. The first graph shows the total 2-5 μm breakthrough caused by a 50% permanent increase after 4h. The breakthrough during the first hour of increase shows that a flow change after 1h appears to cause the highest breakthrough peak for both concentrations. The overall breakthrough (which includes end of run breakthrough) shows no pattern at all. The secondary peak observed in the first experiments did not become more pronounced with the permanently high flow. The second graph displays the breakthrough caused by a 50% gradual flow change after 1, 4 and 20h. The flow changes after 1 and 4 hours only required a run time of 8h and so stop early. Only the 10mg/L results are shown. It can be seen that the overall breakthrough is lower, with the 20h flow change only causing a peak of 100 counts /ml. The 1 and 4h results trend very well, although it would appear that a flow change after 1h falls within the ripening period and so was liable to more varied breakthrough results. There was no failing of the filter at the end of the gradual increase runs, suggesting that these flow increases cause less disturbance to the bed as a whole and so result in better filter performance.
Figure 3: Reduced bed depth experiments
Figure 3

Treatment plants do not use a standard bed depth and so the experiments were repeated using a reduced bed depth of 0.6m. The only influent concentration used was 10mg/L. The 3 graphs show 50% temporary, permanent and gradual flow changes after 1, 4 and 20h. The patterns seen previously are somewhat restored, whereby higher percentage increases cause more breakthrough for all types of flow changes, and changes later in the filter cycles cause more shedding than early increases. Flow changes after 20h cause especially high amounts of breakthrough, as the reduced bed is probably at its maximum sediment capacity already, and so the particles are easily detached. (This is evident as some of the runs were already shedding excess sediment even before the flow change.) As expected, early end of run breakthrough is evident in many of the filter runs, as there was less media for the sediment to be deposited and re-attached in.

Strangely however, gradual flow changes applied to the reduced bed depth cause far higher early breakthrough, especially after the 4h flow change.

The lack of patterns in figures 2 and 3 suggest more complicated reasons behind the breakthrough magnitudes, including several external factors. This can often be seen in water treatment plants whereby not all of the breakthrough is related to backwashing flow changes.

Figure 4

Figure 4 gives a clear indication of the importance of water temperature. The first graph illustrates how a 6°C difference in temperature can affect the breakthrough during a 100% temporary flow change after 4h (Bed depth 1m). It would appear that during periods of warm influent water, the breakthrough is much higher during the actual flow change itself and it also leads to a severe failing of the filter towards the end of the run. This goes against conventional wisdom, which suggests that cold temperatures produce weak flocs which are more easily overcome by the higher shear stress, caused by higher water viscosity. These experiments suggest that although the flocs are smaller at lower temperatures (as seen in jar tests), they are not necessarily weaker, as they can overcome the increased shear stresses. Also, if the flocs are displaced, there is sufficient bed depth for them to be re-attached.

However, when the bed was reduced to 0.6m, the observations were reversed. The second graph breakthrough during a 50% flow increase after 20h, at 15 and 25°C. Here, the colder water produces a higher peak during the flow change and also early failure of the filter. It is possible that the longer lagtime for flocculation at lower temperatures mean that weak flocs pass straight through the shorter bed before stabilising or attaching (Hanson and Cleasby, 1990). This suggests that the combination of water temperature and bed depth are critical considerations for achieving high water quality. There is evidence to suggest that the use of poly-aluminium chloride (PAC) can cause satisfactory flocculation in a wider range of water temperatures and further work must be carried out to investigate how this affects the overall breakthrough.
Comparison of particle breakthrough at different water temperatures. 100% flow increase +4h (50mg/l kaolin)

Using equations reported in Ives and Fitzpatrick 1989, a set of theoretical shear stresses for a range of temperatures and flow changes have been produced, using the assumption that the porosity within the bed reduced by 0.02 per hour. Table 1 gives an idea of how much stronger flocs need to be just to overcome differences in temperature. It can be seen that for the same flow increase, the flocs need to overcome a 22% increase in shear stress at the lower temperature.

<table>
<thead>
<tr>
<th>Time of 50% flow increase</th>
<th>Max. shear stress at 15°C</th>
<th>Max. shear stress at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1h</td>
<td>0.28</td>
<td>0.22</td>
</tr>
<tr>
<td>4h</td>
<td>0.3</td>
<td>0.24</td>
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<td>7h</td>
<td>0.42</td>
<td>0.33</td>
</tr>
<tr>
<td>20h</td>
<td>1.73</td>
<td>1.36</td>
</tr>
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</table>

Table 1: shear stress calculations for different water temperatures
Comparison of breakthrough during static and vibration conditions. 100% flow increase +4h

Figure 5: Breakthrough caused by external vibrations

These final graphs demonstrate a phenomenon which has been researched little, but has shown up at both laboratory and full scale. The first graph shows two filter runs with a 100% flow increase after 4h. However, during the second run, building work was occurring on the floor above. This led to higher base line particle counts and a more unstable breakthrough trend after the flow change, as well as early end of run shedding. This was confirmed as being a direct result of the vibrations with the use of video endoscopy (Ives and Fitzpatrick 1989). Flocs and sand grains could be seen to dislodge with every knock from upstairs. The implications of this for full-scale works is suitably shown in the second graph, whereby demolition of decommissioned clarifiers took place adjacent to operational filters. Between the hours of 9am and 6pm, the breakthrough levels are much higher, and are unrelated to flow changes. This could have serious implications for water quality in high risk Cryptosporidium areas.
GENERAL ANALYSIS

The results detailed in this paper suggest that although flow changes do cause an increase in particle breakthrough, the magnitude of such shedding may be more controlled by external factors such as temperature and vibrations. It has been found that gradual flow increases generally cause less breakthrough and so the recommendations for a 5% per minute maximum increase rate are beneficial in maintaining high water quality levels. The bed depth of the filter is an important variable, as it has a reduced capacity for solid loading and can quickly become unstable after a flow change, leading to the early failure of the filter. The reduced bed depth also requires a slower filtration rate, as the permanent flow increase caused early breakthrough for all variables. The industrial implications of this research is that water treatment works may need to alter their coagulant dosing levels during periods of changing water temperatures, and increase the frequency of the particle count monitoring accordingly, so as to catch any increase in breakthrough levels. Also, care must be taken when planning any construction/demolition work in close proximity to filter beds, so as to cause minimum disturbance to the media. The laboratory experiments have shown to be fairly reliable indicators of full scale performance, and as such are a valuable tool in assessing particle breakthrough behaviour.

CONCLUSIONS

- Flow changes do cause an increase in particle breakthrough
- The magnitude of the shedding is also controlled by external factors
- Vibrations cause increased breakthrough at both laboratory and full scale
- Warm temperatures cause increased breakthrough during flow changes on a deep media bed.
- Cold temperatures cause increased breakthrough in a reduced media depth bed.
- Gradual flow changes (5% per minute) reduce the impact of flow changes and so are recommended for use when introducing flow changes due to backwashing of other filters.

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REFERENCES


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Appendix 2

Anthracite Specification Sheet
Western Carbons Ltd

Anthracite Filter Media Specification Sheet

Use: Treatment of water intended for human consumption
Standard: European EN12909

ISO 9002

Tel 44 0 1269 595925
Fax 44 0 1269 851618
www.westerncarbons.com
ISO 22201

Grade 271

<table>
<thead>
<tr>
<th>Size</th>
<th>1.18 - 2.36 mm</th>
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<tr>
<td>Effective Size</td>
<td>1.32 mm</td>
</tr>
<tr>
<td>Hydraulic Size</td>
<td>1.65 mm</td>
</tr>
<tr>
<td>Uniformity Coefficient</td>
<td>&lt; 1.4</td>
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<table>
<thead>
<tr>
<th>Variance [Maximums]</th>
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</thead>
<tbody>
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<td>Oversize</td>
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</tr>
<tr>
<td>Undersize</td>
<td>5.0</td>
</tr>
<tr>
<td>Effective Size</td>
<td>10.0</td>
</tr>
<tr>
<td>Hydraulic Size</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Physical Characteristics

Source: Welsh Anthracite

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Specific Gravity</td>
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<tr>
<td>Bulk Density</td>
<td>740 kg/m³</td>
</tr>
<tr>
<td>Carbon min</td>
<td>90 %</td>
</tr>
<tr>
<td>Ash max</td>
<td>4.0 %</td>
</tr>
<tr>
<td>Volatile max</td>
<td>5.4 Moh</td>
</tr>
<tr>
<td>Hardness</td>
<td>3.5 Moh</td>
</tr>
<tr>
<td>Grinding Index</td>
<td>42 Hardgrove</td>
</tr>
<tr>
<td>Compression Modulus</td>
<td>min 180 Bar</td>
</tr>
<tr>
<td>Attrition Loss</td>
<td>less than 0.4 % in 100 hours backwashing</td>
</tr>
<tr>
<td>Acid Solubility</td>
<td>below 2.0 % [24 hours in 10% HCl]</td>
</tr>
<tr>
<td>Alkali Solubility</td>
<td>below 2.0 % [24 hours in 10% NaOH]</td>
</tr>
</tbody>
</table>

Geoffrey du Feu Director
Appendix 3

Filterflex parameters
**FilterFlex Parameters**

Viscosity:  
- Summer (25°C) 0.8949x10^{-3} \text{ Ns/m}^2  
- Winter (15°C) 1.1447x10^{-3} \text{ Ns/m}^2

Fluid Density:  
- Summer 997.07 \text{ kg/m}^3  
- Winter 999.13 \text{ kg/m}^3

Floc ratio, removal/deposition: 2

Limiting Shear: 0.5\text{ N/m}^2

Nominal floc size: 5 \text{ microns}

Floc size range ratio: 10

Feed Floc concentration:  
- 0.001 (10mg/l kaolin)  
- 0.005 (50mg/l kaolin)

Time step: 0.02

Max. Time: 24 hours

Step depth: 0.1m

Max. Headloss: 2m

Flow variation at each pulse: 0 (steady state)

Number time intervals per pulse: 2

Displaced floc size: 10\text{ µm}

Submerged particle density:  
- 10\text{ kg/m}^3 \text{ (summer)}  
- 15\text{ kg/m}^3 \text{ (winter)}

Angle of friction for sedimentation: 45°

Sand Media depth: 1m/0.6m

Sand voidage: 0.4

Dual media configuration: 0.5m sand + 0.3m anthracite

Anthracite hydraulic size: 1.65

Anthracite voidage: 0.6
Appendix 4

Video Endoscopy footage

The footage can also be viewed on standard video format, and a copy is held in the Environmental Engineering Dept. University College London.