Technical Report Example from
the Water Industry

The Institution of Chemical Engineers.

Application for Corporate Membership.

Technical Report.
Title: **West Pinchbeck WTW; Biological Filter Air Dosing Optimisation.**

Contents.

## *Introduction and Overview of the Project/Problem.*

In May 2005 I was tasked with the engineering aspects for improving the biological filtration process at West Pinchbeck water treatment works. As part of the overall treatment process at the works there are 6 pressure sand filters installed to remove iron from the raw water. The raw water is sourced from 4 boreholes. The raw water contains approximately 4.0 mg/l of iron. Compressed air is dosed in the common filter raw water inlet pipe as a source of dissolved oxygen. After air dosing the raw water is distributed to the individual filters via butterfly inlet valves. Turbidity is continuously measured at the outlet of each filter. There is provision for post filter dosing of air should this be necessary although this has not been used since the original plant commissioning.

The process had been failing for some time in that filter outlet samples had intermittent high turbidity levels; > 0.1 NTU's. Experience at other treatment works in the supply undertaker's region had led the operational scientist responsible for the area to suggest the following possible causes; inaccurate compressed air dosing, unbalanced inlet flow distribution across the 6 filters and inaccurate turbidity measurement. Inaccurate air dosing was considered the main problem, in that the dissolved oxygen concentration was too high in most cases. It is well documented (reference 2) that the dissolved oxygen be tightly controlled and be between 8 – 10% of saturation for satisfactory treatment. Above this level of dissolved oxygen the iron removal reverts to the physiochemical process. The treatment appears to work reasonably well with inlet flows of 250 – 300 litres / second. Outside this range or when one filter is back-washing then turbidity levels rise.

## *The Process.*

The physiochemical process for the removal of iron from ground waters is well known. (reference 1). I shall review that process here and then outline the biological treatment present at West Pinchbeck.

**The physiochemical process** for the removal of iron involves the oxidation, precipitation and filtration of the dissolved iron. The oxidation of the iron can be achieved using air (oxygen) or a chemical oxidant. The oxidation agent used is dependant on, among other considerations, the pH, the redox environment and the organic content of the water. In the first stage of the process the soluble ferrous iron Fe (II) is oxidised to the insoluble ferric hydroxide FE $(OH)_3$.

$$Fe^{2+} + \tfrac{1}{4} O_2 + 2\tfrac{1}{2}H_2O \rightarrow Fe(OH)_3 + 2H^+$$

The insoluble ferric hydroxide precipitates out of the water and settles on the filter media, in this case sand. It has a reddish-orange colour. Periodically the filter is back-washed to remove the accumulated iron residues.

The kinetics of oxidation of Fe(II) by oxygen are relatively fast at pH 7 and above, provided the ferrous iron is not complexed with organic material. The rate expression is:

$$- d[Fe\ (II)]/dt \ = \ k\ [Fe\ (II)\ ]\ [\ OH^{--}\ ]^2\ P_{O2}$$

The kinetics are first order with respect to the ferrous ion ( Fe II ) and the partial pressure of oxygen ( $P_{O2}$ ) and second order with respect to the hydroxide ion. The hydroxide ion rate confirms the pH dependence. Complexation of the ferrous ion with organic material will slow down the oxidation process.

Turning now to the **biological iron removal process**; it would appear that the presence of iron reducing bacteria facilitate or catalyse the oxidation process depending upon the bacterial species present. The phenomenon has been known for some time (reference 2) and was first observed in conventional physiochemical filters where the retention time for the water within the filter was reduced and yet iron was still being removed. On investigation, a population film of bacteria was found to be present on the sand media. What follows is a discussion of iron reducing bacteria and their respiratory cycle.

A variety of bacteria are involved in a typical filter environment. They can be observed under a microscope and are characterised by their secretions. These secretions may be sheath shapes, typically:

*Sphaerotilus-Leptothrix* group; *Leptothrix ochracea; L. lopholea; L. discophora; Crenothrix polyspora* and others.

Or spirally twisted stalk shapes e. g. *Gallionella ferruginea*.

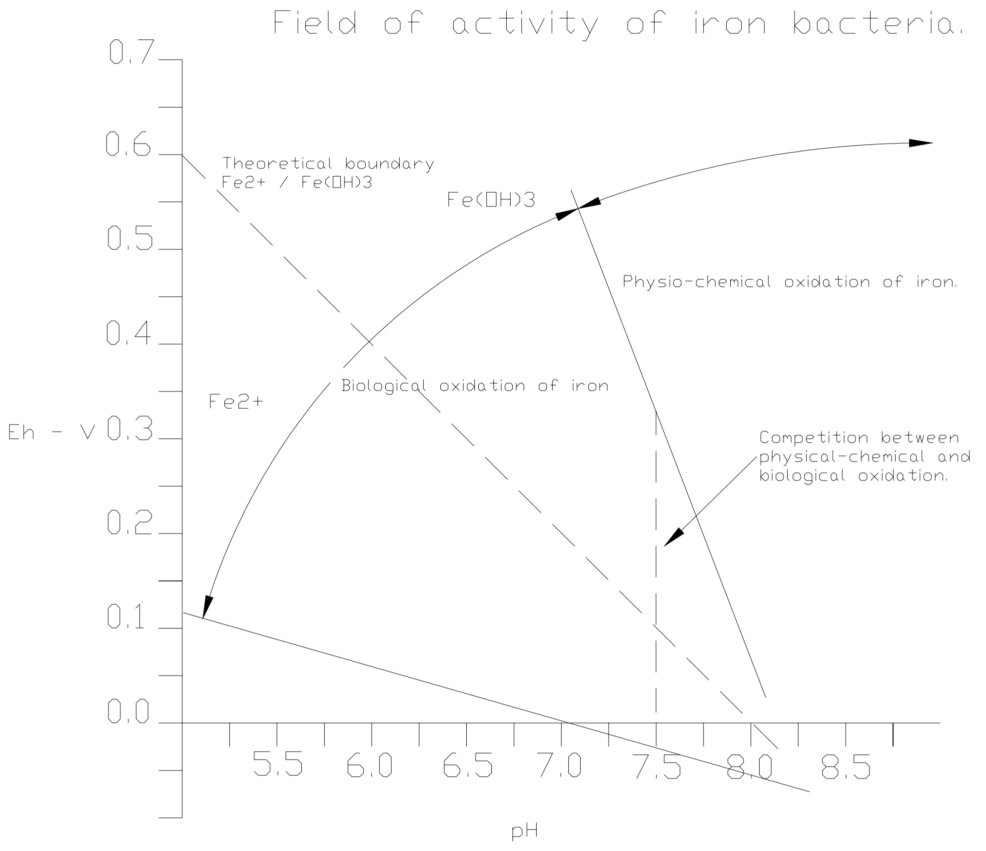
Their field of activity is largely dependant on the pH and rH (redox potential) and the raw water environment. See figure 1 below. The bacteria have the unique property of causing oxidation and precipitation of dissolved iron under pH and rH conditions that are midway between those of natural groundwater and those of conventional physic-chemical iron removal. This property is fundamental to the problem under consideration. Other factors that are instrumental to an effective process are temperature, salinity and organic content of the raw water. These factors will influence the bacterial species that best thrives under any given conditions. The metabolism of these bacteria has been studied since the 1800's. They were once thought to be solely obligate autotrophs with the oxidation of iron being their energy source.

$$4Fe + O_2 + 10\ H_2O \rightarrow 4\ Fe\ (OH)_3 + 8H+ + Q\ cals.$$

The energy released allowing the assimilation and reduction of carbon from dissolved $CO_2$. However, later studies showed this applied only to certain species. Other species may be facultative autotrophs or obligate heterotrophs.

The mechanisms of bacterial oxidation of dissolved iron are again species dependant. Primary intracellular oxidation by enzymes for autotrophic bacteria; *Gallionella sp. Leptrotrix ochracea* and *Crenothrix polyspora* and secondary extracellular oxidation caused by catalytic action of polymers excreted by the bacteria; the stalks and sheaths mentioned above. In all cases the precipitates are slightly hydrated iron oxides, typically y-$FeOOH$ and alpha-$FeOOH$. These precipitates accumulate around the bacterial cells, sheaths, stalks and polymer filaments and form a sludge that is denser in comparison to that formed by precipitates from the conventional physiochemical process. Finally, the accumulated sludge is backwashed from the filters using a reverse flow to release the precipitates.

Figure 1.



## *Engineering Solution to the Problem.*

The engineering solution to the problem of ineffective iron removal treatment was threefold:

1. Installation of individual filter air dosing and mixing equipment to improve control of the dissolved oxygen concentration.
2. Installation of individual filter inlet flow monitoring and control.
3. Installation of new turbidity monitors and sampling facilities.

Individual filter air dosing and mixing was considered the primary solution. The existing equipment for common raw water inlet air dosing was judged to offer only coarse control of dissolved oxygen over the range of inlet flows. Mixing was by a sparge type circular pipe. This crude control of the raw water dissolved oxygen probably caused the filters to operate in the physic-chemical range of activity rather than in the biological range. See appendix for discussion of air dosing of water.

Installation of individual filter flow monitoring and control was considered necessary to balance the raw water flow across the filters available for service. It had long been suspected that the filters closest to the common raw water inlet took more of the flow than those furthest away. Also, filter back washes are initiated on the elapse of a time period not on differential pressure across the filters. Thus, individual filters may have ceased to be effective (high differential) and thereby load the others disproportionately. Individual flow monitoring and control would have the benefit of allowing the back wash period to be optimised as well as balancing the inlet flows. The design inlet flow for each filter is 60 – 70 litres / second.

As part of the project two new control philosophies were programmed into the station programmable logic controller (plc).

- An individual filter inlet flow control loop that uses the existing common inlet flow signal, divides the total inlet flow by the number of filters in service (maximum 6) and modulates the existing filter inlet butterfly valve, using a "nudge and wait" scheme, to achieve an even distribution of the inlet raw water.
- An individual filter air dosing control loop that uses the individual filter flow signal to modulate the air flow to the filter, using a proportional only scheme.

In addition to the above, new filter outlet turbidity monitors were installed along with sample stations (sample taps and sinks in kiosks) for filter inlet and outlet waters. The existing filter outlet turbidity monitors were considered to be inaccurate and obsolete.

### *Impacts of the Solution.*

The impact of the proposed solution was considered for a number of factors:

- Process – effects on other processes in the overall treatment of the water.
- Environmental – effects of construction work, waste materials and to a lesser extend ascetic appearance.
- Legal – water supply obligatory requirements; health & safety issues.
- Economics – whole life costs.
- Operability and maintainability – can the equipment be operated and maintained in a safe and efficient manner?

The impact of the works on the *overall* treatment process was considered to be minimal, in that no new chemical or process had been introduced to the system – only optimisation of an existing part of the system. There may be a beneficial effect on the filter sludge handling plant, a settlement tank that has limited capacity, in that, optimisation of the biological filtration may require fewer backwashes and thereby more time for settlement. However, the works was intrusive in that the initial filter to be modified for the mixer and flow sensor installation, and sampled (see legal aspects below) was off line for 2 weeks. Fortunately, the station has enough spare capacity to accommodate a filter out of service. More intrusively, a 1 day station shutdown was required to install a modified plc programme and extend busbars in a 240 volt distribution board that the new kiosks.

The impact of the works on the environment was assessed with respect to disturbance of flora and fauna; construction activity, dust and noise; construction waste materials and ascetic appearance. The works was wholly within the boundaries of an existing water treatment works so a protected species survey was unnecessary. The works were 90% mechanical and electrical with very little dust or noise pollution and minimal waste materials. The station is in a remote part of Lincolnshire and is landscaped on the boundaries with hedges and large scrubs. As such, the general public passing by on adjacent footpaths and a minor road would not easily see the new kiosks.

The legal aspects of the works were considered and included the necessity to comply with water supply regulations with respect to materials in contact with potable water and hygiene regulations for persons coming in contact with potable water equipment. Compliance with health and safety legislation for construction works is also mandatory. The works came under the full remit of the Construction and Design Management (CDM) regulations including notification to HSE. A design phase health and safety plan was produced and on appointment of a principle contractor a construction phase plan. The main safety issues were working and height and heavy lifting.

The whole lift costs are always considered when designing a solution to a process problem. The solution in this case did not increase station costs (chemicals or materials) and may in fact save a small amount on power costs by more efficient use of compressed air, Manpower costs for operations and maintenance should also reduce given a more effective and efficient process – less call out and intrusive work.

The equipment installed will not present any new operational tasks once commissioned and only minor new maintenance tasks. The equipment is situated at ground level where operational and maintenance activities can be carried out in a safe manner, albeit outdoors.

## ***Mechanical and Electrical Equipment.***

Raw water flow measurement.
ABB Aqua Probe flow measuring devices complete with transmitters were used to measure the individual filter flows. The probe type sensors, in preference to conventional full pipe diameter magnetic flow-meters, allowed the installation without an extensive station shutdown, as the filter inlet pipes could not be isolated individually. The probe sensors could be installed with the filters on-line using hot tapping techniques and a wrap around pipe clamp. The inlet pipes had sufficient straight lengths of pipe upstream and downstream to ensure accurate measurement. The probe sensors are themselves a magnetic flow device and have a claimed accuracy of plus or minus 1% of scale.

Air flow control valve.
The compressed air flow to each filter was controlled by a V port ball valve manufactured from stainless steel. The ball, in this application, has a 60 degree port that gives good linear control over the full flow range. The valves are manufactured by Triac Control Valves. Further the valves are actuated to allow automatic control of individual filter air flow from the station plc controller.

Turbidity measurement.
Individual turbidity meters were installed to replace 5 of the 6 existing turbidity monitors; these were considered unreliable and obsolete. The 6th meter, monitoring the filter F, is new and was installed in 2005. The monitors have sensor and controller modules and are manufactured by Hack Lange. The sensor module has a bubble trap and a tungsten filament white light suitable for low – medium turbidity levels, 0.001 – 100 NTU's. The measurement method is 90 degree scatter and complies with USEPA 180.1 standard. Signals from the monitors are wired back to the station plc, for indication / telemetry purposes only.

Air /water mixing.
In order to facilitate mixing of the compressed air and water, static inline mixing were installed in the individual filter inlet pipes. The static mixers are manufactured by Statiflo Ltd. The mixers have no moving parts (as the name implies), the mixing is achieved by means of a number of angled vanes internal to the pipe – see appendix for photo. Two air injection lances are provided to place the air in the optimum position at the entrance to the mixer. The outlet mix is better than 95% at water flows of 40 – 70 litres / second.
A sample point has been provided post mixer to facilitate initial setting up and testing of the system; for dissolved oxygen concentration.

### *Testing and commissioning.*

Commissioning of the new equipment proceeded over a number of months due to operational constraints. The various stages of commissioning were:

1. The in-line motionless mixers were commissioned as each filter was returned to service immediately after installation. The exception was the first mixer to be installed – this required materials in contact sampling and approval. Subsequent mixers were installed and commissioned based on the approval of the first.
2. The individual filter flow meters were tested, set up and commissioned.
3. The individual filter turbidity monitors were tested, calibrated and commissioned.
4. The new control programmes were loaded into the station plc. This created some problems as the existing human machine interface (HMI) was not compatible with the modified programme. A temporary HMI was installed for the display and control of the new equipment.
5. The filter flow balancing control loop was tested and commissioned.
6. The individual air dosing system was commissioned on manual and then automatic control.

I shall comment on the flow measurement / control and the air dosing / control only.

The individual filter flow measurement revealed a hydraulic anomaly: in that the filter furthest away from the raw water inlet appeared to take the bulk of the flow, that is, filters A & B were taking 80 – 90 litres / sec compared with filters D & E taking 20 – 30 litres / sec. The filter design flow is 70 litres / sec. The flow balancing control improved this condition to give a more even distribution of inlet flow to the filters in service, typically; given a total inlet flow of 300 litres / second with six filters in service the individual filter flows would be 50 litres / second plus or minus 3 litres / second.

The filter air dosing, initially commissioned on manual control, allowed optimisation of the dissolved oxygen dose to each filter. The target dose was 0.6 mg/l as $O_2$ at the inlet to the filters. As the individual filter flow was now relatively stable for normal station inlet flows (300 l/s) the target DO's were achieved. On automatic control the target air flows were maintained within an acceptable range of 0.5 – 0.7 mg/l. Some hysteresis was found in the actuated air flow valve; about 2 – 3% of travel. This reduced the sensitivity of the dose rate modulation to small changes in inlet flow.

### *Outcome and conclusions.*

Did it all work and solve the problems? Conditionally, yes! On the positive side:

- The filter flow balancing is a great success. The individual filters now receive an optimum raw water flow closer to their design flow. At the time of writing further work is proposed to automatically put filters in / out of service thereby allowing filter design flows of 70 litres / second regardless of the station inlet flow.
- The new turbidity monitors and sampling arrangements are an improvement on the previous equipment and facilitate accurate monitoring of the filter process.
- The individual filter air dosing and mixing equipment performed to meet the design criteria, in that, filter inlet dissolved oxygen is dosed at the desired rate provided the filter raw water flow is above 50 litres / second.

Issues arising from the works:

- Turbidity levels do not appear to have significantly improved. This may be for a number of reasons:
    - The filter media may need investigation – it may be contaminated, blocked or channelled.
    - The biological process may not be suitable, given the raw water chemistry, to achieve the desired outlet turbidity. The original works design included for blending with low turbidity waters from another water treatment works.
    - The biological filtration process may not be entirely clear in that contact times and backwash frequency times need addressing.
- Further work is required on the station plc programme to optimise the filter backwash frequency and individual filter flows.

- Recent measurements of the raw water dissolved oxygen show a concentration of 0.56 mg/l: that makes control of filter inlet dosed DO very tight.

## *Appendix 1.*

### *Water air dosing.*

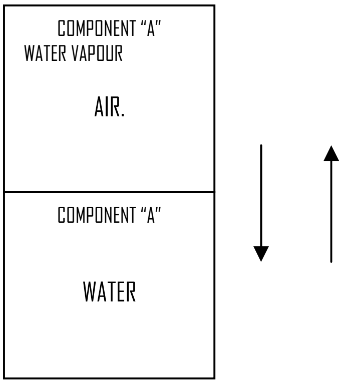
The process of dissolving air into water is common in the water supply industry. The process may involve simple aeration, using for example a cascade that would not only oxygenate the water but also release dissolved gases, typically carbon dioxide and sulphur dioxide. Alternatively, air may be directly injected into the water stream, using compressed air bubbles, as in this case.

The concentration of dissolved oxygen in a sample of water is dependent on a number of factors of which temperature and barometric pressure are of particular interest. For a temperature of 15 oC and pressure of 755 mbar/Hg the DO concentration is 10.00 mg/l. The target concentration for this process is approximately 0.6 mg/l (from observation and experience of the works scientist).

The theory of gas transfer has two aspects:

- Equilibrium partitioning of the chemicals
- Mass transfer rate across the air / water interface.

Henry's law describes the equilibrium system:



$$K\ eq. = \frac{(A)\ air}{(A)\ \ aq.}$$

(A) air: activity of A , gas phase
(A) aq: activity of A , aqueous phase
(B) K eq: equilibrium constant.

At constant temperature and 1.0 atmosphere the gas behaves ideally giving (from equation above):

$$H = Keq. = P_A / Y_A\,[A]$$

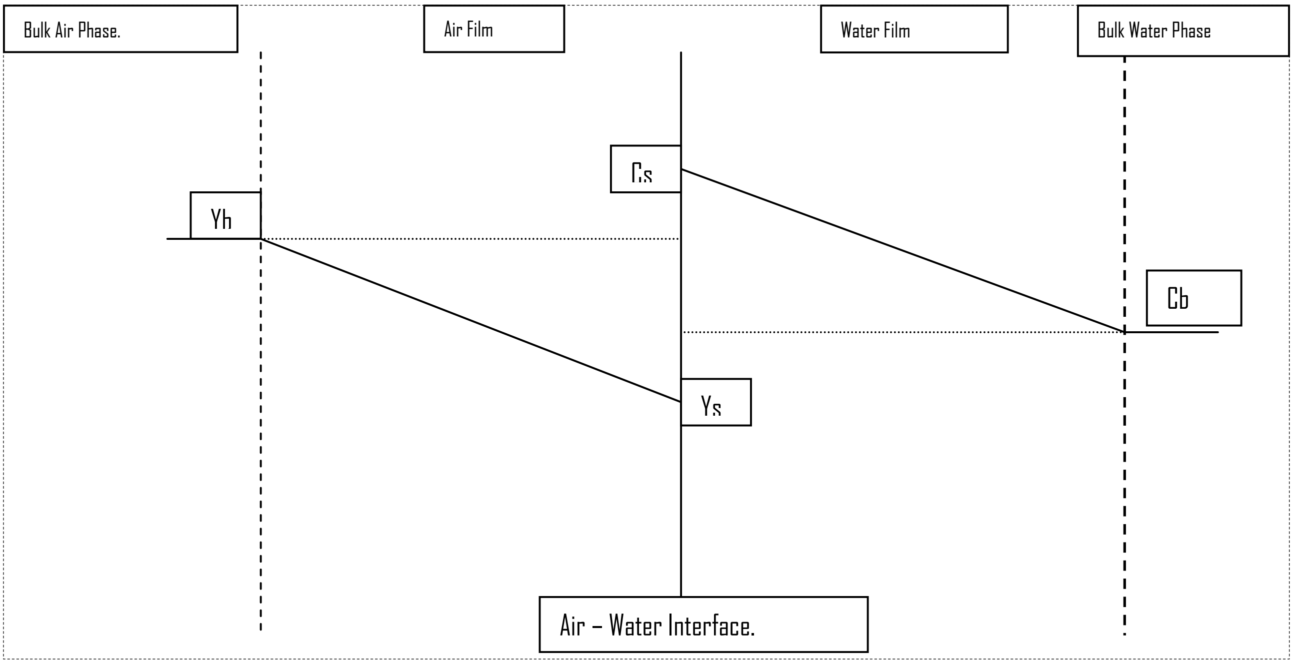
Where H = Henry's Law constant (atm – L/mol) of A.
$P_A$ = partial pressure of A in gas phase. (atm.)
$Y_A$ = activity of A in aqueous phase
[A] = aqueous phase molar concentration of A (mol/L).

The above equation could be used to calculate the amount of air required to achieve the target dissolved oxygen concentration under ideal conditions **but** a number of assumptions would have to be made, not least that the mass transfer of gas was perfect. The assumptions would include:

- The concentration of oxygen in air remained constant and did not vary with temperature and barometric pressure.
- The concentration of dissolved oxygen in the raw water was zero and did not vary significantly.

- The chemical environment of the raw water did not effect the diffusion of oxygen.

With regard to the mass transfer rate of oxygen gas the driving force between one phase and the other is derived from the displacement of the system from equilibrium. There must be a concentration gradient from the air to the water for diffusion to occur. The air / water interfaces are at the inner and outer surfaces of the air bubbles – a bubble has two surfaces, whereas, out of interest, a cavity (in a volume of water) has only one. The diagram below illustrates the concentration gradients.



For absorption of the air: the concentration inside the air bubble Yb is higher than the concentration at the air / water interface Ys; so the gradient is downhill to the interface. Similarly, the concentration at the water side of the interface Cs is greater than the bulk water concentration Cb; again the driving force of diffusion is downhill. Henry's law can be used to relate Ys to Cs as: Ys = H C s.

Fick's law can be applied to show that the flux (the mass transferred per unit time per unit of interfacial area) is proportional to the concentration gradient.

As an aside, I surmise that as the concentration gradient decays (> 0) the bubble collapses and it's contents are fully dissolved in the water.

## *Appendix 2: Dose rate calculation.*

For initial testing and setting up purposes the following estimate of air dose rate was used.
Given:
Oxygen concentration in air = 21%.
Density of air at STP = 1.293 kg / m3.

Ram of air – 30
Ram of oxygen – 13.

Amount of oxygen per litre of air.

16/30 x 1.296 x 21/100 = 0.145 grams O2 / litre of air

Desired dose rate is 0.6 mg/l as O2.

Number of litres of water dosed for 1 litre of air to achieve desired dose rate.
145/0.6 = 242 litres of water.

For a **station raw water flow** of say **300 litres / second** then:
300/242 = 1.2397 litres / sec of air or **4.463 m3 / hour of air @ STP.**

For 6 filters in service this equates to 4.463 / 6 = **0.744 m3 / hour of air** per individual filter vessel.
It should be stressed that the above figure is only an estimate and assumes perfect absorption of the air into the water.

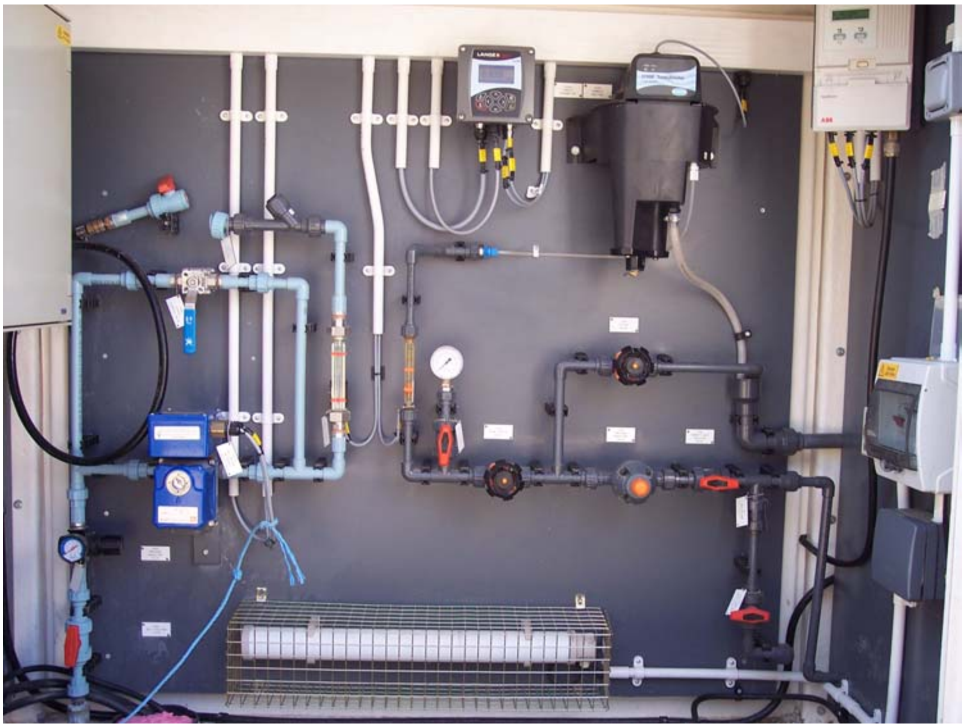
## *Appendix 3: Photograghs.*

West Pinchbeck WTW: Biological Filters.

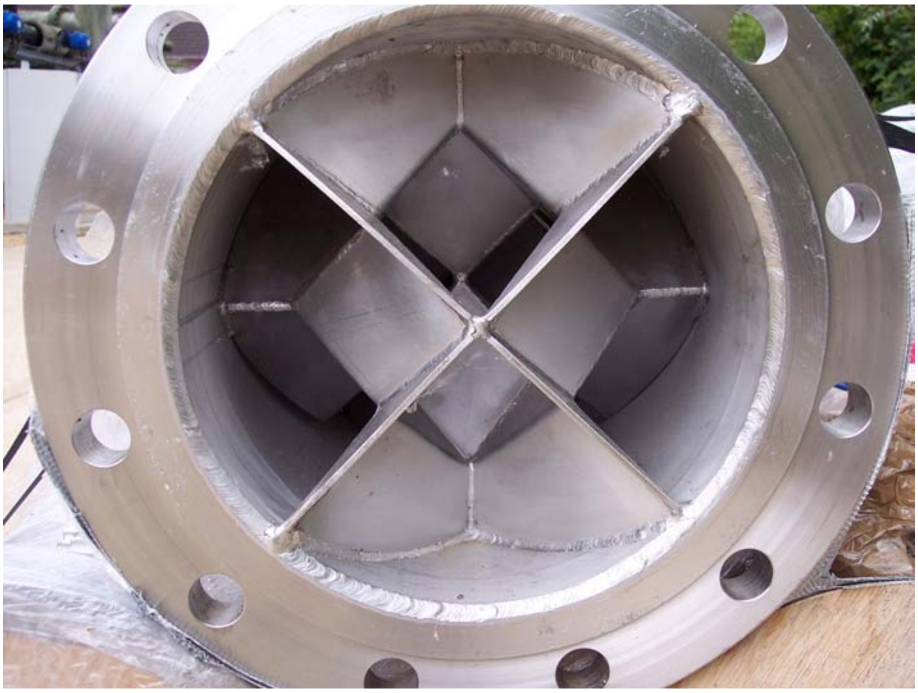
A Typical Filter Before Modifications.

Typical filter post installation.

Typical filter air dosing kiosk.



Motionless mixer elements.



Filters post installation.

## *Appendix 4: References.*

Reference 1:  Water Quality & Treatment. Fifth edition 1999, American Water Works Association.

Reference 2: From Conventional to Biological Removal of Iron and Manganese in France. Journal of AWWA Volume 84, number 4, 1992. Pierre Mouchet.

Reference 3: Atkins' Physical Chemistry. Seventh edition 2002, Peter Atkins & Julio de Paula.