Experiences in integrity testing ultrafiltration membranes at a large potable water treatment works

S. Oxtoby
Vivendi Water Partnership, Three Valleys Way, Bushey, Hertfordshire WD23 2LG, UK
(E-mail: steve.oxtoby@veoliawater.co.uk)

Abstract The Clay Lane Water treatment works of Three Valleys Water, in the south east of England, is currently the world’s largest ultrafiltration works with a capacity of 160 Ml/d. It utilises ultrafiltration membranes constructed as hollow fibres with a number of membrane elements in a pressure housing. The plant has been operating since spring 2001. The decision to install the system was made in anticipation of the introduction of tighter regulations on Cryptosporidium in water supplies in the UK. Once a decision was made to proceed with a membrane system the ability to monitor the integrity of the system and to repair problems became a crucial design parameter that was a critical part of membrane selection. The need to include a system affected the design of the filtration units offered by manufacturers. The available systems for integrity testing are reviewed and the reasons for selecting the system adopted are discussed. These include particle counting and the dosing of test particulate loads. The different forms of air passage integrity tests are discussed and the displaced air flow system used is described. Once a failure has been detected it must be traced so that the fault can be repaired. This procedure is described together with the techniques of pin repair of damaged fibres. At Clay Lane and other membrane filtration sites the backwash water from membrane cleaning is recovered using a secondary membrane system. Currently the secondary system operates in the same integrity testing regime as the primary system and the secondary filtrate is returned ahead of the primary membrane system. The relative merits of this system, or the alternative of adding the recovered water to the filtrate are discussed.

Keywords Integrity testing; membrane; potable water; ultrafiltration

Introduction Clay Lane Water Treatment Works is currently the largest ultrafiltration system in the world, with a capacity of 160 Ml/d. It was constructed by OTVB and Norit Membrane Technology for Three Valleys Water, with project management by Vivendi Water Partnership, and started operation in April 2001. Three Valleys Water supplies potable water to 3 million customers in the area to the north and west of London UK and Clay Lane is one of the company’s major sources, supplying 15% of average output.

The source is groundwater from a chalk aquifer and is affected by surface water ingress during periods of high rainfall. To reduce risk the company decided to install a membrane filtration system culminating in a contract award in 1999. The membrane filtration system uses dead-end filtration through capillary fibres. The incorporation of an integrity testing system was seen as a key feature throughout the specification and design phases.

The integrity testing method used is the displaced air flow test in which the volume of rate of flow of air passing through the membranes is measured and compared with the flow expected by diffusion on an intact membrane system. Should the integrity be found to be compromised the affected membrane elements are identified and may be isolated for later repair. A high flow alarm provides for automatic shutdown of significant leaks. The test must be carried out offline and so is not continuous. The lack of a continuous monitoring facility means that the frequency of testing must be sufficient to ensure that failures are detected before they have built up to a significant number. There needs to be an allowance made for failures that may have already occurred but will not be detected until the affected
unit is next tested. The test also proves the sealing performance of the various seals separating the feed and filtrate.

After removal from the filtration unit the membrane elements are examined for leaks and leaking fibres are repaired by inserting pins into the open ends of the filaments. Once reassembled the whole unit is retested before going back into supply.

**Description of Clay Lane WTW**

Clay Lane receives water from 8 borehole abstraction sites located some distance from the works. The boreholes abstract from the chalk aquifer underlying the district and are all located along the valley of the river Colne. The abstraction is run as a group and has a maximum abstraction capacity of 210 ML/d. However, the maximum capacity of the existing works is 160 ML/d and this matches the capacity of the distribution network. The annual abstraction licence is 118.5 ML/d as an annual average. Hence the works can only run at peak capacity to match maximum demand for a short period in summer.

The existing treatment works consisted of ozonation and granular carbon filtration before super- and de-chlorination. The ozone system is fed by oxygen partially generated by a pressure swing absorption system. The super- and de-chlorination system is adequate but there is a desire to be able to reduce the use of chlorine if possible.

The membrane filtration plant consists of 32 primary filtration units, each of which operates as an individual pressure filter in dead-end mode with its own flow control. The filtration units are of the Norit Membrane Systems design using the X-Flow XIGA concept elements. This uses poly-ethersulphone ultrafiltration membranes constructed as capillaries with a bore of 0.8 mm and the microporous membrane layer on the bore side. The pore size of these membranes is approximately 25 nm and so they are capable of retaining all protozoa, cysts, spores and bacteria together with the majority of viruses. The capillary fibres are assembled in elements 1,500 mm long and 200 mm diameter in a UPVC shell, with a structure to distribute feed and filtrate and enclosed by epoxy potting at both ends. Each element contains approximately 9,300 fibres. The feed is into the bore of the capillaries and the filtrate is collected from the shell side into a central filtrate tube. Four elements are placed in a horizontal 6 m long pressure vessel or housing, and the filtrate tubes are connected together by push in inter-connectors sealed by double o-rings. By-pass tubes spaced around the filtrate tube convey feed water from the ends of the housing to the central elements. The filtrate is withdrawn from both ends of the housing by the filtrate tube extending through the end cap. Each filtration unit has 12 such housings and includes 1,680 m² of membrane area. The maximum gross flux rate is 132 litres per square metre per hour or lmh ($3.67 \times 10^{-5}$ m/s). Kruithof et al. (1998) described a similar installation at Heemskerk in North Holland and concluded that integrity monitoring was necessary if using membrane systems as a disinfection barrier.

Each filtration unit is washed with a water only backwash at a frequency related to the throughput and turbidity, and regularly undergoes a chemically enhanced backwash routine in which either acid or alkali is added to the backwash to achieve pH 2 or pH 12 and soaked for 600 seconds. These activities produce wastewater, which is recovered by four secondary recovery units. Each recovery unit has 12 such housings and includes 1,680 m² of membrane area. The maximum gross flux rate is 132 litres per square metre per hour or lmh ($3.67 \times 10^{-5}$ m/s). Kruithof et al. (1998) described a similar installation at Heemskerk in North Holland and concluded that integrity monitoring was necessary if using membrane systems as a disinfection barrier.

Each filtration unit is washed with a water only backwash at a frequency related to the throughput and turbidity, and regularly undergoes a chemically enhanced backwash routine in which either acid or alkali is added to the backwash to achieve pH 2 or pH 12 and soaked for 600 seconds. These activities produce wastewater, which is recovered by four secondary recovery units. Each recovery unit has 12 such housings and includes 1,680 m² of membrane area. The maximum gross flux rate is 132 litres per square metre per hour or lmh ($3.67 \times 10^{-5}$ m/s). Kruithof et al. (1998) described a similar installation at Heemskerk in North Holland and concluded that integrity monitoring was necessary if using membrane systems as a disinfection barrier.

Each filtration unit is washed with a water only backwash at a frequency related to the throughput and turbidity, and regularly undergoes a chemically enhanced backwash routine in which either acid or alkali is added to the backwash to achieve pH 2 or pH 12 and soaked for 600 seconds. These activities produce wastewater, which is recovered by four secondary recovery units. Each recovery unit has 12 such housings and includes 1,680 m² of membrane area. The maximum gross flux rate is 132 litres per square metre per hour or lmh ($3.67 \times 10^{-5}$ m/s). Kruithof et al. (1998) described a similar installation at Heemskerk in North Holland and concluded that integrity monitoring was necessary if using membrane systems as a disinfection barrier.

**Process selection**

The key parameters that were considered in selecting a process were the regulatory
approval of the membrane system, which had to be approved by the UK Drinking Water Inspectorate for contact with potable water (Regulation 25 approval), the compatibility of the membrane with chlorinated water and the availability of an effective integrity test that was sufficiently sensitive.

The design of the integrity testing system was left to the vendors but the key parameters in the assessment of competing systems were the sensitivity of the test and the ability to locate and isolate faults readily. Systems offered included a pressure decay test, an air flow test and a surrogate challenge test using 1 μm carbon particles and a particle counter. Particle counting without the addition of a surrogate challenge was totally unfeasible because of the typical low particle counts in the feed water. The challenge test was rejected on the grounds of inadequate sensitivity and because it did not provide any means of locating the breakage. It also places a heavy reliance on the particle counter whilst not verifying that the dosed water contains the required concentration of particles. Adham et al. (1995) reviewed various testing procedures and concluded that the particle counting techniques would significantly increase the costs of large-scale membrane systems because of the number of counters that would be required. Pressure decay tests were not selected on the grounds of a relatively poor sensitivity compared with the airflow test due to the rate of the expected pressure decay. Also, depending on the system design the process of locating breaks could take much longer.

**Membrane integrity test**

The membrane integrity test that is used is based on the principle that when a microporous membrane is wetted air cannot flow through it unless the differential pressure exceeds the bubble point. This was established by Bechold (1908). As the pore size of the ultrafiltration membranes is approximately 25 nm, the bubble point is considerably above the pressure that the membrane system can withstand. Depending on the values taken for the contact angle and other relevant factors the pressure of 100 kPa used is the bubble point corresponding to a pore size of 0.8 to 4 μm.

Below the bubble point air will only flow through defects or by diffusion due to the pressure gradient across the membrane and the sensitivity of the test depends on being able to distinguish the two. If too large a membrane area is tested at a time the diffusive flow will mask the flow through defects and it may only be possible to detect the effect of multiple defects. The diffusive flow is affected by the condition of the membranes and will change as fouling occurs and so a clear distinction is required.

In the design of the system at Clay Lane, the test is performed after draining the feed side of the membrane system. The drain valve is opened and an air pressure of 100 kPa applied. Once this step has been completed the flow test valve on the filtrate side is opened and the water in the filtrate side is displaced by air through the flow meter. The flow meter measures the water flow displaced by the air. Proof testing and information from many sources indicated that this test was much more sensitive than monitoring a decay in pressure on the feed side. The pressure on the feed side is maintained throughout the test.

Initially the flow monitored is high because some water remains on the feed side of the membranes after the draining process. The air pressure acts as a driving pressure to pass this through the membrane until it is gone and so the flow pattern exhibits a rapid decline to a relatively steady level, during which an average measurement is taken. The test cannot be continued indefinitely because the filtrate side begins to fill with air and the flow meter will ultimately run empty.

After a satisfactory test the unit is refilled from the filtrate side by a backwash and vented.
Membrane repair method

Once a failure has been detected it must be located. This is done by extending the test while the filtrate valves on the membrane housings are closed in turn. When the correct housing is isolated the flow is reduced and the housing can be left isolated until a convenient time to repair it. One housing can be isolated per unit before the flow rate has to be reduced (8% of membrane area is then isolated).

In order to repair membranes they must be removed from the unit. All four membrane elements in the housing are removed and placed in a bath. The filtrate connection is sealed at one end, and the other end is connected to a low pressure air supply. The damaged fibres are indicated by a stream of bubbles rising from their ends at the potting seal.

The leaks are sealed by closing off the ends of the affected fibres by inserting pins and in the current repair method these are glued into the fibre by using a solvent cement and polysulphone repair pins.

After the pins have been inserted the element is retested to ensure that the repairs are effective and the elements replaced in the housing. When the unit is fully assembled it is retested and, if successful, returned to service.

Failure history

During commissioning it was expected that there would be an initial period when the failure rate would be high as the membranes were first put to use. It was then expected that this would level off as initial manufacturing faults were cleared. This concept was incorporated into a takeover test, which required that any such period be completed before contractual takeover. It was found however that the failure rate was not elevated initially.

The principal factor that has been found to increase the rate of breakage is a high transmembrane pressure.

The number and frequency of the membrane breakages has never been enough to signif-

Figure 1  Integrity test schematic
icantly compromise the removal efficiency as the rate of testing has always exceeded the rate of breakage.

The repair of membranes has become a rather larger operation than was envisaged at the outset and some difficulties have emerged. In particular some membrane elements have been removed, repaired and appear satisfactory, but when replaced in a unit will not pass. This phenomenon has caused much work to ensure that the problem is not related to o-ring seals and other causes. The current hypothesis is that the unit test applies the pressure to the fibre lumens but the element test in the repair bath pressurises the outside of the fibres. For tears in the fibre this may close the defect in the element test and make the fault harder to locate. It is planned to construct a single element tester that would allow individual elements to be tested in the same way as the installed test and this may reduce the time and frustration caused.

Control strategy for large sites
A theoretical calculation of the likely number of broken fibres required to reduce the plant log removal value (LRV) to 5 (99.999% removal) produced an estimate of 25 fully broken fibres. This was backed up by proving trials using Bacillus subtilis spores of approximately 1 µm size and MS2 bacteriophages of 27 nm carried out by KIWA for NMT. These showed that the removal efficiency of an intact membrane was >6.9 LRV for the spores. However, this removal efficiency is more a function of the number of spores used in the pilot test with none being detected in the filtrate, and the removal was effectively absolute. A higher efficiency would thus be demonstrated were it practicable to test at a higher feed concentration. Panglisch et al. (1998) reported similar results for the same membrane design and others but only tested intact fibres. In the KIWA study the removal efficiency of a pilot plant using full scale elements was tested both with Bacillus subtilis and MS2 bacteriophages. These indicated that a broken fibre for each membrane element would reduce the efficiency to 3.3 LRV. The tests and the calculations indicated a water leakage flow in typical conditions of approximately 2 l/h (5.5 × 10⁻⁷ m³/s) for a fully cut fibre. The proof that the integrity test could readily detect and shutdown such defects led to confidence that an extremely high level of removal efficiency could be maintained by a daily test of the whole plant even at breakage rates orders of magnitude greater than the guaranteed values.

The testing of the airflow test on a rack containing 24 membrane elements indicated that the diffusion would lead to a flow of about 50 l/h but a rack with a cut fibre would have a flow of 300 l/h. Thus the flow through the defect would be 250 l/h. This indicates a ratio of about 125:1 for the values of airflow to water flow through the same defects and with a 100 kPa air test pressure. If the minimum LRV was to be 5 for a minimum flow of 80 Ml/d the water leakage flow would need to be below 9.26 × 10⁻⁶ m³/s equivalent to 16 broken fibres. This would be equivalent to an air leakage flow of 1.175 × 10⁻⁵ m³/s (4,167 l/h). However, on a full plant each rack would also contribute 50 l/h. With 64 racks this would mean an additional 3,200 l/h of airflow.

The conclusion is that if the total of all of the airflow tests approaches 3,200 l/h the plant is fully intact and that as long as it is below 7,200 l/h the plant would achieve a 5 log removal should there be a sufficient challenge. A total airflow of 3,600 l/h would indicate 6 LRV and 45,500 l/h 4 LRV. It should be remembered that there are some large assumptions and generalisations in these figures and so unwarranted precision should not be claimed. However it is reasonable to state the claimed removal to the nearest half log removal.

As a result of these considerations the integrity control strategy was revised to enable a tighter control to be achieved of the total leakage flow, with minimum disruption to plant operation. Rather than simply taking offline those units passing a flow above a fixed limit the overall leakage rate from all of the tests is actively managed to keep it as low as possible.
Whilst units with a very high flow are still automatically isolated, when the overall leakage rate is low units with a marginal level of failure are allowed to stay online and the faults located and isolated without the need for an automatic shutdown.

The tests carried out by KIWA showed a removal of the MS2 phage which were a surrogate for viruses at 4.7 LRV on intact membranes and proportionally reduced on the tests with a reduced integrity. This indicates that if the membrane integrity is maintained the removal efficiency for virus-sized particles will be maintained at a high level and that the membrane can be viewed as a disinfection barrier. This offers the prospect of reducing the existing disinfection process at Clay Lane from super- and de-chlorination to marginal chlorination only. The marginal chlorination would still be required to ensure that the water was protected in distribution and to treat ammonia from certain sources.

**Control strategy for small sites**

Clay Lane is a large works and the strategy outlined above is appropriate for such a works where the large number of intact systems dilute the effect of failures. However, for small sites a single membrane failure could result in a compromise in efficiency at the highest levels. For a 5 Mld site the air leakage rate indicating a 5 LRV efficiency would be 260 l/h which is equivalent to a single broken fibre. The diffusion rate on a plant of this size would be typically 50 l/h. Since a failure should be allowed for in the period before the next test it is arguable whether a plant of this size can guarantee a 5 LRV. To do so would require the testing to be more frequent which would affect productivity. Also there is no room for tolerance of low level failure. Any compromise must result in a shutdown to maintain a high standard of efficiency.

Alternatively, the view could be taken that it is reasonable to operate small sites at a lower efficiency and guarantee 4 LRV. At this level the defects flow could be increased by 10 times and the leakage could be managed as described above. It should be noted that even at 4 LRV the removal efficiency is substantially better than typically achieved by conventional water treatment processes.

**Secondary recovery options**

Clay Lane and many other sites employ secondary recovery systems to reduce the volume of the backwash waste generated. At Clay Lane the primary membrane systems generate up to 5 Mld of washwater each day and this is reduced to 160 m³ by a secondary membrane system using the same type of membranes at a lower flux. At Clay Lane the filtrate from this system is returned to the head of the works despite the inclusion of an integrity test for the secondary system because at the time of designing the works there was no experience on which to take any other option.

The secondary system is not only a small plant, it is also treating a more concentrated feed. If 4 LRV is all that can be guaranteed and the main plant is achieving 5 LRV the overall efficiency would reduce to 4 LRV were the secondary filtrate to go forward to supply.

The operation of the secondary units is generally vital to the continued operation of the plant and without secondaries the washing of primaries will quickly become inhibited and the plant will have to shut down. If the secondary systems were taken out of service on an integrity test failure the whole plant is then vulnerable to a shutdown. To avoid this situation the best option would be to divert the flow to the head of the works on a secondary integrity test failure. Since provision for this increased return flow would have to be made in the design of the plant there will be no saving to be made in having a system where the flow could go into supply when the integrity is good. Consequently, it is preferable to return the recovered water at all times and reduce the dependence on the secondary
integrity test.

Conclusions
The airflow test is the most sensitive method of testing the integrity of ultrafiltration membranes but should be employed at an appropriate frequency to ensure a high level of integrity is maintained.

Membrane failures need to be readily repairable and improvements are possible in the design of filtration units and repair methods to improve this.

By maintaining a high level of integrity of an ultrafiltration system, it can operate as a disinfection barrier. At large plants it is possible to control on the basis of an overall leakage target with safeguards against gross failure. Small plants will require either more frequent testing to maintain a guarantee of maximum efficiency or a reduced guarantee expectation.

Where secondary recovery in a separate membrane system is employed it is necessary to return the recovered water to the head of the works to ensure that the removal efficiency is not compromised.

Acknowledgements
This paper could not have been published without the assistance of colleagues from Three Valleys Water, Vivendi Water Partnership, OTVB and Norit Membrane Technology who provided help in developing and operating the membrane system and shared their experiences. The permission of Three Valleys Water and Vivendi Water Partnership for the preparation and publication of this paper is gratefully acknowledged.

References