Ultrafiltration to supply safe drinking water in developing countries: A review of opportunities

Citation for published version:

Digital Object Identifier (DOI):
10.1007/978-1-4020-9139-1_16

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Appropriate Technologies for Environmental Protection in the Developing World

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
ULTRAFILTRATION TO SUPPLY DRINKING WATER IN INTERNATIONAL DEVELOPMENT: A REVIEW OF OPPORTUNITIES

J. Davey and A. I. Schäfer

School of Engineering and Electronics, The University of Edinburgh, William Rankine Building, The King’s Buildings, Edinburgh EH9 3JL, United Kingdom

Email Andrea.Schaefer@ed.ac.uk Ph +44 131 650 7209 Fax +44(0) 131 650 6781

Abstract

One of humanity’s biggest problems at present are millions of preventable deaths in developing countries. Most of those deaths are caused by microorganisms, often from sewage contaminated drinking water. Hence, technology to remove such contaminants is a first step to solving the problem. One such technology is ultrafiltration (UF). UF is a membrane filtration process in which water is pushed through a physical filter with a transmembrane pressure supplied by a pump or gravity. The pore size of such membranes is such that bacteria and most viruses can be effectively retained. As a consequence, this process has the ability to disinfect water physically and hence prevent water related disease and death from microorganisms.

In this paper the performance of existing UF membranes and systems will be reviewed in terms of pathogen removal, water productivity (system capacity and flux), specific energy consumption per volume of water produced, which affect cost. Specific needs of systems to be installed and operated in developing countries as well as opportunities for the global community will be outlined.

Keywords: Ultrafiltration, developing countries, decentralised treatment, renewable energy, pathogen removal, water supply.

1 Introduction

Water related problems are increasing around the globe, with regard to both quantity and quality. In the current international Decade for Action ‘Water for Life’ (2005-2015) (UN 2006) and the United Nations Millennium Goals (UN 2005) policy makers, practitioners and researchers are searching for ways to address the problems of millions of water related deaths each year, most of which affect children (Gleick 2002). In developing countries water and sanitation infrastructure is still lacking which is the major cause for this problem. While technology has long been available, common obstacles are ‘lack of investment, lack of political will, and difficulty in maintaining services’ (Montgomery and Elimelech 2007). Many communities in developing countries are vastly lacking infrastructure such as water pipes, an electricity grid, or access to a knowledge base to design, build and maintain treatment facilities, this poses a significant challenge. In now developed countries similar conditions prevailed prior to industrialisation and the construction of a sewer and water supply infrastructure, commonly referred to as public health engineering (Strang 2004). This infrastructure remains in service today, although not without problems and in many remote locations in developed countries (such as aboriginal communities in Central Australia, Islands in the Mediterranean, some rural areas in Europe) remain without access to safe drinking water and or rely on expensive water delivery by truck or boat.

A secondary problem after microbiological pollution is the presence of natural or man-made contaminants such as arsenic, selenium, uranium, fluoride, nitrate or boron, which often result in crippling health effects or death due to chronic exposure (Schwarzenbach et al. 2006). Those compounds require advanced treatment technologies for reliable continuous removal as opposed to conventional methods such as sand filtration.

In developed countries, micropollutants such as endocrine disrupting chemicals and pharmaceuticals have become a concern, often also due to sewage contamination of drinking water sources. This has resulted in a questioning of the suitability of existing infrastructure (Weber 2006) as all water is being treated to a very high drinking water standard and then used for many applications such as toilet flushing, cleaning, car washing, and irrigation which do not require such high standards. While it is clear that the debate on this topic is ongoing, it invites the opportunity to take a different approach in developing countries and, at least in remote locations, trial a decentralised approach. UF lends itself as a very suitable technology for such an approach and it is in this spirit the technology is reviewed with regards to performance and likely energy demands of such systems.

2 Ultrafiltration for provision of clean drinking water

2.1 Principle of ultrafiltration (UF)

Membrane systems achieve a physical disinfection of water by physically sieving the waterborne organisms that are larger than the smallest pore size. Any material that is smaller passes through the membrane with the clean water or permeate. Subsequently, disinfection can take place without the need for chemicals. The assessment of the pore size and their distribution within a membrane are very important in the microorganism removal potential of the membrane (Jacangelo et al. 1991). Because of the primary application of UF to retain macromolecules, the ‘pore size’ of a UF membrane is usually expressed as molecular weight cut-off (MWCO) in Dalton (Da: g/mol). This molecular weight cut of can be converted into an actual pore size, which is commonly used for membranes with larger pores and UF is in the range of 0.005 to 0.04 μm (von Gottberg and Persechino 2000). Therefore, viruses, which have a larger diameter (0.01-0.1 μm) can be retained, although smaller species may pass through the more open membranes. Bacteria are much larger than the pores (1-10 μm) and their retention is hence not a problem as long as the filter is intact. A comparison of UF membrane pore size with the size of bacteria, viruses, water molecules and ions is illustrated in Figure 1. An overview of some common microorganisms and their sizes is given in Table 1.

Membranes have been used in sanitation and sterilization processes due to their ability to perform this physical disinfection. While microfiltration (MF, pore size 0.1-0.45 μm) have been shown to retain small bacteria such as Pseudomonas diminuta (Waterhouse and Hall 1995), MF cannot usually retain viruses. However, the pore size classifications of those two membranes overlap somewhat and often depend on manufacturer preferences. In consequence, it is important...
to know the pore diameters of specific materials and apply a healthy level of caution when selecting a membrane.

The transmembrane pressure, which is the driving force in UF, varies from -0.5 bar to about 3-4 bar. A negative pressure (suction pressure or vacuum) is applied in submerged systems, in which the membrane is immersed in a water tank and the product water then sucked through the membranes to the permeate side. This configuration is common in high solids applications such as membrane bioreactors for wastewater treatment (DiGiano et al. 2004) or high turbidity surface waters as the process allows simultaneous sedimentation of particles. In general, pressure increases as the pore size decreases due to the higher membrane resistance at a given productivity (flux). Flux is the permeate flow normalised per membrane area and ranges for UF from as low as 50 L/m².h to as high as 1000 L/m².h. While high fluxes reduce the cost of membranes due to the reduced need in membrane area, fouling and hence cleaning and maintenance costs tend to increase. Pilot trials with specific waters are recommended to determine realistic flux values and establish pre-treatment needs.

2.2 Ultrafiltration applications

UF is increasingly used to produce safe drinking water (Laîné et al. 2000), which can partially be attributed to increasing problems with microbiological contamination (in particular Giardia and cryptosporidium). In fact, low pressure membrane processes such as UF and MF are capable of producing drinking water that falls in line with the standards set by the Surface Water Treatment Rule (SWTR) (Jacangelo et al. 1991). This combined with the decreasing costs of membranes (between 1994 and 2000 membrane costs fell by approximately 70%) has resulted in an increased adaptation of the technology (Laîné et al. 2000). However, in 2003, the majority of large scale plants are installed in the US (about 50%) while only 3 of 450 large scale (>400 m³/d) applications are in Africa (Adham et al. 2005). It is evident that a significant market potential is yet to be satisfied. Less information is available on small scale systems and hence this paper aims at summarizing the most prominent small scale UF systems.

A number of other important applications of MF and UF are

1. coupling with chemical additives such as coagulants or powdered activated carbon if smaller contaminants such as natural organic matter or micropollutants are to be removed;
2. pre-treatment for nanofiltration (NF) and reverse osmosis (RO) to minimise fouling and prolong optimal operation conditions and membrane lifespan (Vedavyas 2007).

This is an important consideration for international development applications where long term operation of systems with minimal maintenance is important (Schäfer et al. 2007); and

(3) wastewater treatment and reuse, especially membrane bioreactors (MBR). Increased concern about contaminants in wastewater discharge and in some cases water recycling applications are driving such change combined with the advantage of a smaller footprint of membrane technology compared to conventional treatment. This area is a significant opportunity for international development for the control of wastewater and hence the contamination of water supplies (DiGiano et al. 2004).

2.3 Retention of pathogens (viruses and bacteria)

Removal of bacteria and viruses is describes as log removal (LR) which is defined in equation (1).

\[
LR = -\log \left( \frac{n_{\text{final}}}{n_{\text{initial}}} \right)
\]

where \(n_{\text{final}}\) is the final virus count and \(n_{\text{initial}}\) is the initial virus count. Given the varying shapes and sizes of bacteria and viruses (see Table 1), retention is often specific to the type of microorganisms provided its size is similar to the pore size. Tests are rarely performed with viruses and hence little data is available for specific species but common model viruses rather. Microorganism removal with predominant ‘conventional’ water treatment technologies such as slow sand filtration or biological filtration is generally low and unreliable as virus retention in such filters is often dependent on the establishment of a biofilm. For example, sand filters achieved a 2 log removal (99%) for the MS-2 (0.028 \(\mu\)m) and 3 log (99.9%) for the PRD-1 (0.065 \(\mu\)m) bacteriophages (Yahya et al. 1993). The level of microorganisms must be reduced or inactivated to an extent so that they do not pose a threat to health when consumed and these results fall short of the guidelines set by the SWTR where, to be compliant, a 3 log removal or inactivation of Giardia needs to be achieved and a 4 log (99.99%) removal of viruses (Yahya et al. 1993).

The removal of viruses and bacteria from water supplies using low-pressure membranes has been well documented (Jacangelo 1995). Due to the nominal pore size of a UF membrane the majority of bacteria (\(>4\) log) and viruses (\(>4\) log) can be removed from a contaminated drinking water source.

Table 2 and Table 3 show the LR of viruses for a number of commercially available UF systems. Reported virus removal averages about 4 log (99.99%) in a reported range of 0.5 (MF) to 6 log with coagulation pre-treatment. Drouiche et al. (2001) have reported a 6 log removal of bacteria and viruses using UF (99.99%) for the PRD-1 membrane (0.065 \(\mu\)m) bacteriophages.

For example, sand filters achieved a 2 log removal (99%) for the MS-2 (0.028 \(\mu\)m) and 3 log (99.9%) for the PRD-1 (0.065 \(\mu\)m) bacteriophages. This can be partially attributed to increasing problems with microbiological contamination (in particular Giardia and cryptosporidium). In fact, slow sand filtration or biological filtration is generally low and unreliable as virus retention in such filters is often dependent on the establishment of a biofilm. For example, sand filters achieved a 2 log removal (99%) for the MS-2 (0.028 \(\mu\)m) and 3 log (99.9%) for the PRD-1 (0.065 \(\mu\)m) bacteriophages (Yahya et al. 1993). The level of microorganisms must be reduced or inactivated to an extent so that they do not pose a treat to health when consumed and these results fall short of the guidelines set by the SWTR where, to be compliant, a 3 log removal or inactivation of Giardia needs to be achieved and a 4 log (99.99%) removal of viruses (Yahya et al. 1993).
infected individuals for a short period of time (Grabow et al. 1999). Coliphages are widely used as model viruses. They are easy to work with, give acceptable results and, most importantly, are non-hazardous. Their size is also advantageous as it is very similar to pathogenic viruses (Otaki et al. 1998). For example, Herath et al. (1998) used RNA coliphages to replicate pathogenic viruses, their size and shape is very similar to that of pathogenic enteroviruses, along with four strains of E. coli phages, T4, QB, MS2 and fr. The T4 E. coli was used as it has a very irregular shape while the other three have icosahedron shapes, which is similar in shape to a sphere. E. coli is a thermophilic coliform which indicates faecal pollution from warm blooded animals (Ashbolt et al. 2001). Table 1 shows the size of micro-organisms used to model viruses.

<table>
<thead>
<tr>
<th>Micro-organism</th>
<th>Eq. Diameter (µm)</th>
<th>Length (µm)</th>
<th>Width (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4</td>
<td>0.019</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MS2</td>
<td>0.025</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QB</td>
<td>0.08</td>
<td>2.25</td>
<td>-</td>
</tr>
<tr>
<td>E. coli K12</td>
<td>0.98</td>
<td>4.77</td>
<td>0.82</td>
</tr>
<tr>
<td>P. putida</td>
<td>1.1</td>
<td>2.53</td>
<td>0.96</td>
</tr>
<tr>
<td>E. coli K12/λ</td>
<td>1.82</td>
<td>2.42</td>
<td>1.00</td>
</tr>
<tr>
<td>E. coli K12/δ</td>
<td>1.82</td>
<td>3.84</td>
<td>1.08</td>
</tr>
<tr>
<td>Alcaligenes</td>
<td>1.62</td>
<td>2.75</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Table 1 Sizes of Micro organisms used to model viruses (adapted from (adapted from Herath et al. 1998)).

Figure 2 Equivalent diameters of a number of micro-organisms and typical membrane pore sizes, adapted from Herath et al. (1998).

Figure 3 Equivalent diameters of smaller micro-organisms and the nominal pore sizes of a number of commercially available membranes.

Looking at the sizes presented in Table 1 one can see that many microorganisms will not be challenging to remove. Removing the smaller viruses or phages effectively is more difficult, however. Figure 2 shows the difference in size between the sizes of selected micro-organisms and the pore sizes of typical UF and MF membranes. Organisms larger than the membrane cut-off lines are retained. The area shown of specific interest in Figure 2 is the region where MF cannot remove viruses effectively (see Figure 3 for more detail). However, in this domain some UF membranes can successfully remove these viruses based on size exclusion.

In summary, based on bacteria and virus removal data available in the literature, UF is an ideal process to alleviate the problem of water related disease and death in developing countries, although further work to specifically investigate the retention of some common viruses in the field, system maintenance, membrane integrity and component failures would be beneficial.

3 UF systems in international development

Despite the obvious potential of UF to solve the problem of safe water in developing countries, to date very few such technology are making their way into the developing world on a long-term basis. UF systems are being used in humanitarian situations, an example being the donation of a number of small-scale UF/MF units for emergency disaster relief, such as the Sumatran Tsunami in 2004 (Zenon 2005). During natural disasters damage is often caused to the sanitary infrastructure. Therefore, surface waters can become rapidly contaminated with faecal microbiota. If this water is to be used for drinking and is left untreated then an epidemic is likely to break out. As a result, UF can be used to remove these microorganisms to a suitable level and provide a sustainable alternative to bottled water. Unit operation in such disaster situations is generally short term and hence provides an opportunity for technologies that are not yet proven in terms of long term technical sustainability. Oxfam, for example, is seeking technologies for disaster relief that can operate for period of one year and that are ‘disposable’ meaning that they will not normally be recovered after a period of service (Bastable 2007).

Water supply systems sought for international development are typically ‘low-tech’. Naturally, countries are poor, disposable incomes, if any, low and the lack of ‘public health infrastructure’ calls for the development of a sewerage and water distribution infrastructure as in the developed world. The required investment for such infrastructure is enormous and in consequence little progress is made. An alternative is to implement novel concepts such as decentralized UF systems, particularly in areas where distances from urban areas are large and infrastructure (water distribution systems and electricity grid installations) are expensive. This provides an area of potential investigation for the development of autonomous low-pressure membrane systems powered by renewable energies. To evaluate feasibility and potential costs it is of interest to review existing UF systems, their performance and energy consumption, in particular.

3.1 Existing ultrafiltration systems

Table 2 summarises a number of UF and MF system that are commercially available. Those systems are not necessarily suited to international development applications and most require existence of infrastructure such as an electricity grid. Some are designed for sewage rather than drinking water treatment. However, most of those systems can potentially be adapted into renewable powered systems for remote applications. A positive side-effect of the high quality water produced by UF is that any remaining viruses or regrowth of microorganisms in this water can be effectively controlled by disinfection processes as turbidity, which often interferes with disinfection processes, has been removed. This ultimately reduces costs of such post-treatment and the generation of a residual disinfectant concentration.
Table 2: Table of selected commercial UF systems with published data (max. capacity, typical transmembrane pressure (TMP), log virus removal) unpublished/calculated specific energy consumption (SEC) (based on operation at max. capacity).

<table>
<thead>
<tr>
<th>#</th>
<th>Company</th>
<th>System</th>
<th>Membrane</th>
<th>Max Capacity [m³/h]</th>
<th>TMP [kPa]</th>
<th>SEC [Wh/m³]</th>
<th>Log Virus Removal</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KWS</td>
<td>KfK-4</td>
<td>Koch P+W Hollow Fiber Membrane</td>
<td>33.3</td>
<td>240</td>
<td>410</td>
<td>4 (Koch Membrane Systems (1) 2009)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>KWS</td>
<td>P-6</td>
<td>Koch P+W Hollow Fiber Membrane</td>
<td>25.4</td>
<td>240</td>
<td>615</td>
<td>4 (Koch Membrane Systems (2) 2009)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>US Filter (Memcor)</td>
<td>EFC-600</td>
<td>-</td>
<td>5.5</td>
<td>-</td>
<td>-</td>
<td>- (Siemens Water Technologies Corp 2007)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>US Filter (Memcor)</td>
<td>EFC-424</td>
<td>-</td>
<td>11.0</td>
<td>-</td>
<td>-</td>
<td>- (Siemens Water Technologies Corp 2007)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>US Filter (Memcor)</td>
<td>EFC-1200</td>
<td>-</td>
<td>11.0</td>
<td>-</td>
<td>-</td>
<td>- (Siemens Water Technologies Corp 2007)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Separation Dynamics</td>
<td>Extran Model E†</td>
<td>Extran 400</td>
<td>0.78</td>
<td>150</td>
<td>641</td>
<td>- (Separation Dynamics)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Zenon</td>
<td>ZBox-S 50</td>
<td>ZeeWeed 1000</td>
<td>11.4</td>
<td>-</td>
<td>3.5</td>
<td>Deason 2007; Zenon (1)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Zenon</td>
<td>Ecmaglad</td>
<td>-</td>
<td>2.93</td>
<td>-</td>
<td>-</td>
<td>Deason 2007; Zenon (1)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Pall Corporation</td>
<td>AP-1</td>
<td>Microra Hollow Fiber Membrane</td>
<td>7.0</td>
<td>250</td>
<td>214</td>
<td>4.5-6 (Pall Corporation (1))</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Pall Corporation</td>
<td>AP-2</td>
<td>Microra Hollow Fiber Membrane</td>
<td>12.0</td>
<td>250</td>
<td>855</td>
<td>4.5-6 (Pall Corporation (1))</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Pall Corporation</td>
<td>AP-3</td>
<td>Microra Hollow Fiber Membrane</td>
<td>11.3</td>
<td>280</td>
<td>1197</td>
<td>4 (Pall Corporation (1); Pall Corporation (5))</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Norit</td>
<td>Perfection</td>
<td>K-Pure Aquaflex</td>
<td>2.0</td>
<td>300</td>
<td>513</td>
<td>4 (Norit (1); Norit (2); Norit (3))</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Norit</td>
<td>Ecmaglad</td>
<td>International (PCI-BMS)</td>
<td>20.0</td>
<td>300</td>
<td>2308</td>
<td>Deason et al 2001</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Norit</td>
<td>Ecmaglad</td>
<td>Extran A2</td>
<td>10.8</td>
<td>240</td>
<td>686</td>
<td>Deason et al 2001</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Norit</td>
<td>Ecmaglad</td>
<td>X-Flow S30</td>
<td>8.0</td>
<td>200</td>
<td>86</td>
<td>Deason et al 2001</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Holto</td>
<td>Amjet-hydron</td>
<td>-</td>
<td>0.85</td>
<td>-</td>
<td>-</td>
<td>Sokol 2004</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Holto</td>
<td>Amjet-hydron</td>
<td>-</td>
<td>0.85</td>
<td>-</td>
<td>-</td>
<td>Sokol 2004</td>
<td></td>
</tr>
</tbody>
</table>

† reliable data for SEC determination is to date difficult to access and varies significantly depending on controls and operating parameters as well as assumption in estimation. This topic requires a more in-depth analysis. For this reason data from Table 3 for membranes only was used in this paper.

3.2 Performance of membranes in terms of productivity and energy consumption

In order to determine power requirements of a UF system using a specific membrane needs to know the transmembrane pressure and feed flow. The power consumption of a UF system can be calculated as (Mulder 1996)

\[ P = \frac{Q \cdot \Delta P}{\eta} \] (2)

Where Q is the volumetric feed flowrate (m³/h), \( \Delta P \) is the transmembrane pressure (N/m²) and \( \eta \) is the pump efficiency (typically 0.5 - 0.8), giving a power value in Watts (Mulder 1996). The majority of the energy usage of such membranes is due to the applied transmembrane pressure, while monitoring and control equipment as well as fouling control also need to be considered. Energy requirements of control systems have been neglected in calculations for the purpose of this paper.

The specific energy consumption (SEC) of a system is defined as the energy consumed in the production of a unit volume of water. This is based on the power consumption of the system, in this case simplified to the dominating unit which is the pump. SEC is defined as

\[ SEC = \frac{IU}{Q} \] (3)

Where I is the current of the pump (A), U is the voltage (V) and Q is the permeate flowrate (m³/h). However, since P = IU, power can be substituted into equation (3)

\[ SEC = \frac{P}{Q} \] (4)

For calculation in this paper, flux data (if not published) was calculated using equation (5) with the maximum capacity of the membrane under question in order to give the maximum productivity of the system. This results inevitably in the minimum SEC value.

\[ J = \frac{dV}{dt} \] (5)

When the membrane was classified with a MWCO it was converted to μm by using the Einstein-Stokes Equation. Einstein-Stokes Equation is defined in Equation 6, adapted from Woch (1993).

\[ \frac{d}{M} = \frac{3.7 \times 10^{-10}}{M_{w} \cdot \eta} \] (6)

where \( M_{w} \) is the molecular weight cut off expressed (Da, g/mol) and the d is the equivalent pore diameter (μm).

investigation. Overall a substantial 4 log virus removal can be achieved with 'maximum capacity' SECs as low as 100 W.h/m², which is about 10-20 times lower than for a scale brackish water desalination system using UF as pretreatment (Schäfer et al. 2007).

Table 3 Table of commercially available membranes used in various systems (max. capacity, membrane area, TMP, Log removal) and published/calculated data (flux, pore diameter, SEC).

<table>
<thead>
<tr>
<th>#</th>
<th>Manufacturer</th>
<th>Name</th>
<th>Membrane Type</th>
<th>Max Capacity (m³/h)</th>
<th>Area [m²]</th>
<th>TMP [kPa]</th>
<th>Flux [L/m²h]</th>
<th>Pore Diameter [µm]</th>
<th>Log Virus Removal</th>
<th>SEC [Wh/m²]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Koch Membrane Systems</td>
<td>1</td>
<td>NSF 52-35 PM/P</td>
<td>4.5</td>
<td>32.1</td>
<td>210</td>
<td>143</td>
<td>0.016</td>
<td>5</td>
<td>Koch Membrane Systems (1) 2004</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Koch Membrane Systems</td>
<td>2</td>
<td>NSF 87-35 PM/P</td>
<td>7.3</td>
<td>60.5</td>
<td>215</td>
<td>145</td>
<td>0.018</td>
<td>4</td>
<td>Koch Membrane Systems (1) 2004</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Koch Membrane Systems</td>
<td>3</td>
<td>NSF 10-35 PM/P</td>
<td>11.6</td>
<td>80.9</td>
<td>240</td>
<td>143</td>
<td>0.018</td>
<td>4</td>
<td>Koch Membrane Systems (1) 2004</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pall Corporation</td>
<td>1</td>
<td>Microra CL12-3020</td>
<td>3.5</td>
<td>10.7</td>
<td>300</td>
<td>327</td>
<td>0.005</td>
<td>3</td>
<td>Pall Corporation (1); Pall Corporation (2)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Pall Corporation</td>
<td>2</td>
<td>Microra CL15-3020</td>
<td>3.5</td>
<td>23</td>
<td>300</td>
<td>152</td>
<td>0.005</td>
<td>3</td>
<td>Pall Corporation (1); Pall Corporation (2)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Pall Corporation</td>
<td>3</td>
<td>Microra CL15-3040</td>
<td>7.3</td>
<td>23</td>
<td>260</td>
<td>320</td>
<td>0.005</td>
<td>3</td>
<td>Pall Corporation (1); Pall Corporation (2)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Pall Corporation</td>
<td>4</td>
<td>Microra CL15-3040</td>
<td>16</td>
<td>34</td>
<td>300</td>
<td>471</td>
<td>0.004</td>
<td>3</td>
<td>Pall Corporation (1); Pall Corporation (2)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Pall Corporation</td>
<td>5</td>
<td>Microra LN-3010</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.006</td>
<td>4</td>
<td>Pall Corporation (4)</td>
</tr>
<tr>
<td>9</td>
<td>Pall Corporation</td>
<td>6</td>
<td>Microra LN-3110</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.006</td>
<td>4</td>
<td>Pall Corporation (4)</td>
</tr>
<tr>
<td>10</td>
<td>Pall Corporation</td>
<td>7</td>
<td>Sepha</td>
<td>11.5</td>
<td>13.9</td>
<td>280</td>
<td>813</td>
<td>0.032</td>
<td>4</td>
<td>Pall Corporation (1); Pall Corporation (2)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Pall Corporation</td>
<td>8</td>
<td>Sepha 020D</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.006</td>
<td>4</td>
<td>Pall Corporation (4)</td>
</tr>
<tr>
<td>12</td>
<td>Hydranautics</td>
<td>1</td>
<td>Hydrapac</td>
<td>4.6</td>
<td>35</td>
<td>152</td>
<td>150</td>
<td>0.016</td>
<td>3</td>
<td>Hydranautics</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Hydranautics</td>
<td>2</td>
<td>Hydrapac</td>
<td>6.6</td>
<td>46</td>
<td>152</td>
<td>140</td>
<td>0.016</td>
<td>3</td>
<td>Hydranautics</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>High Select 3000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.005</td>
<td>3</td>
<td>(Hydranautics)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>High Select 5000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.007</td>
<td>3</td>
<td>(Hydranautics)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Lliqui-Flux</td>
<td>1</td>
<td>Membrane</td>
<td>4.8</td>
<td>61</td>
<td>70</td>
<td>120</td>
<td>0.016</td>
<td>3</td>
<td>Lliqui-Flux</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Ziron</td>
<td>1</td>
<td>Ziron 6000</td>
<td>1.97</td>
<td>41</td>
<td>202</td>
<td>51</td>
<td>0.006</td>
<td>2</td>
<td>Ziron 2007; Ziron (1)</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Ziron</td>
<td>2</td>
<td>Ziron 6000</td>
<td>3.87</td>
<td>56</td>
<td>200</td>
<td>85-86</td>
<td>0.018</td>
<td>3.5</td>
<td>Ziron 2007; Ziron (1)</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Norit</td>
<td>1</td>
<td>Aquaflex</td>
<td>1.25-25 PSF</td>
<td>17.5</td>
<td>35</td>
<td>400</td>
<td>484</td>
<td>0.026</td>
<td>4</td>
<td>Norit (Norit (2))</td>
</tr>
<tr>
<td>20</td>
<td>Norit</td>
<td>2</td>
<td>Aquaflex</td>
<td>1.25-25 PSF</td>
<td>3.3</td>
<td>35</td>
<td>400</td>
<td>100</td>
<td>0.016</td>
<td>3</td>
<td>Norit (4)</td>
</tr>
<tr>
<td>21</td>
<td>Norit</td>
<td>3</td>
<td>Aquaflex</td>
<td>1.25-25 PSF</td>
<td>3.3</td>
<td>35</td>
<td>400</td>
<td>100</td>
<td>0.016</td>
<td>3</td>
<td>Norit (4)</td>
</tr>
<tr>
<td>22</td>
<td>UltraFiber</td>
<td>1</td>
<td>UltraFiber</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
<td>0.5</td>
<td>(Semb Water Technologies Corp)</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>UltraFiber</td>
<td>2</td>
<td>UltraFiber</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
<td>0.5</td>
<td>(Semb Water Technologies Corp)</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Nitto Denko</td>
<td>1</td>
<td>NTU-3054</td>
<td>15</td>
<td>30</td>
<td>300</td>
<td>500</td>
<td>0.004</td>
<td>-</td>
<td>Nittodenko (Nitto Denko)</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Nitto Denko</td>
<td>2</td>
<td>NTU-3054</td>
<td>7</td>
<td>14</td>
<td>300</td>
<td>500</td>
<td>0.004</td>
<td>-</td>
<td>Nittodenko (Nitto Denko)</td>
<td></td>
</tr>
</tbody>
</table>

5. SEC calculations are based on published typical performance data which is likely to deviate from real performance. It is essential that more data on power consumption be made available to assess the actual performance of such membranes.

![Figure 4 Specific energy consumption and flux versus pore diameter (from Table 3).](image)

![Figure 5 Log virus removal as a function of membrane pore diameter (commercial see Table 3) and experimental studies (see Table 4)).](image)

### 3.3 Comparison of specific energy consumption with desalination systems

Since UF is a low pressure process (typically 1.0 – 5 bar), the required energy is significantly lower than that in nanofiltration and reverse osmosis units that operate in the range 5 – 20 bar and 10 - 100 bar, respectively (Mulder 1996). UF is ideal for the treatment of surface waters, while NF or RO are required if salinity or trace contaminants are of concern.

Schäfer and Richards have designed an autonomous desalination system that uses UF as a pretreatment step (Richards and Schäfer 2002, 2003; Schäfer et al. 2005, 2007; Schäfer et al. 2001; Schäfer and Richards 2005) driven by renewable energy for use in remote areas. There are a number of systems, which have coupled renewable energy, such as photovoltaics and wind power, in desalination applications to varying degrees of success. The performances of these systems with regards to specific energy consumption (SEC) vary significantly ranging from 1-2 kWh/m² (Schäfer et al. 2007) to 26 kWh/m² (Joyce et al. 2001). Since NF/RO operates at far
higher pressure than UF, the SEC of UF would naturally be significantly lower. As result UF has a huge potential to be used cost effectively as a decentralised system in remote communities and in international development.

4 Conclusions

The review in this paper confirms that UF is a very appropriate choice for resolving the issue of lack of access to safe drinking water in developing countries as well as in disaster relief. The nature of this process in that it is reliable, simple, and energy efficient, makes it suitable for small decentralised systems. The energy requirements can be met in various ways using grid power (where available), renewable resources, generators, handpumps or sometimes gravity. If desalination is required such a system provides an excellent pre-treatment and acts as a double barrier for micro-organisms.

The implementation and maintenance of such systems and their technical sustainability remains to be dealt with. A possible approach would be for some companies focusing investment on selected countries in which, with the aid of donors or aid agencies, many similar systems are installed. With a large number of systems in certain areas it becomes workable to have maintenance personnel based in the area which then can assist with training local operators and offering initiatives such as a ‘mobile membrane cleaning’ service. We are the first generation that can look extreme and stupid poverty in the eye, look across the water to Africa and elsewhere and say this and mean it: we have the cash, we have the drugs, we have the science - but do we have the will? Do we have the will to make poverty history?

(Bono, 2005)

We indeed have the technology and we have the knowledge to solve water problems in developing countries.

5 Acknowledgements

The contributions of many colleagues and companies to the queries looking for small scale UF systems are acknowledged.

6 References


Novi (1). X-Flow introduces the Perfector-E. In From Website: http://www.novi.nl/?RubriekID=2216.


Pall Corporation (1). Power Generation Products. In From Website: http://www.pall.com/power_product_list.asp.


Environmental Science and Technology 41, 1003.


