MEMBRANE FILTRATION – A CASE FOR MOBILITY

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ABSTRACT

This paper presents a number of case studies where membranes have been used for potable supply. One case study is for the Australian Defense Force on a remote training camp. The second case study is for an Australian mining company to cater for growth. The last case study was a UF plant to replace an existing clarifier and filter system

The paper discusses the challenges of each scheme and how these challenges were overcome using membranes as the key process technology.

The paper will demonstrate that membrane filtration including ultra-filtration or Reverse Osmosis are established and robust technologies that can meet these unique challenges by providing compact, high rate and versatile water treatment plants to cater for a wide range of raw water conditions

KEYWORDS

Reverse Osmosis, Ultra-filtration, Drinking Water, Mobile Plants, GE Water

1 INTRODUCTION

Who actually discovered / developed membrane filtration is not known, but credit seems to be given to the Austrian Professor called Richard Adolf Zsigmondy in 1927, whilst working at the University of Göttingen, Germany.

Zsigmondy was initially a colour chemist with a specific interest in the colouring of glass (he worked for Schott Glass) and subsequently he developed his career in colloidal chemistry. Membrane filters were first commercially produced by Sartorius GmbH a few years later.

2 MEMBRANE PROCESS

There are four main membrane processes:

Reverse Osmosis (RO) is the tightest possible membrane process in liquid/liquid separation. Water is in principle the only material passing through the membrane; essentially all dissolved and suspended material is rejected. The more open types of RO membranes are sometimes confused with nanofiltration (NF).

True NF rejects only ions with more than one negative charge, such as sulfate or phosphate, while passing single charged ions such as sodium and chloride. NF also rejects uncharged, dissolved materials and positively charged ions according to the size and shape of the molecule in question. Finally, the rejection of sodium chloride with NF varies from 0-50 percent depending on the feed concentration.

In contrast, "loose RO" is an RO membrane with reduced salt rejection. This effect has proven desirable for a number of applications where moderate salt removal is acceptable since operating pressures and power consumption are significantly lowered. So, in exchange for less than complete salt removal, costs are reduced.

Ultra filtration (UF) is a process where the High Molecular Weight Compounds (HMWC), such as protein, and suspended solids are rejected, while all Low Molecular Weight Compounds LMWC pass through the membrane freely. There is consequently no rejection of mono- and di-saccharides, salts, amino acids, organics, inorganic acids or sodium hydroxide.

Microfiltration (MF) is a process where ideally only suspended solids are rejected, while even proteins pass the membrane freely. There is, however, quite a gap between real life and this ideal situation.

Table 1: Comparing Four Membrane Processes

	Reverse Osmosis	Nanofiltration	Ultrafiltration	Micro filtration
Membrane	Asymmetrical	Asymmetrical	Asymmetrical	Symmetrical
Thickness Thin film	150 μm 1 μm	150 μm 1 μm	150 - 250 μm 1 μm	10-150 μm
Pore size	<0.002 μm	<0.002 μm	0.2 - 0.02 μm	4 - 0.02 μm
Rejection of	HMWC, LMWC sodium chloride glucose amino acids	HMWC mono-, di - and oligosaccharides polyvalent neg. ions	Macro molecules proteins polysaccharides viruses	Particles, clay bacteria
Membrane material(s)	Cellulose Acetate Thin film Poly Amide	Cellulose Acetate Thin film Poly Amide	Ceramic PSO, PVDF, Cellulose Acetate, Thin film	Ceramic PP PSO, PVDF
Membrane Module	Tubular spiral wound, plate-and-frame	Tubular, spiral wound, plate-and-frame	Tubular hollow fiber, spiral wound, plate-and-frame	Tubular hollow fiber
Operating pressure	15-150 bar	5-35 bar	1-10 bar	<2 bar

Asymmetric membranes are characterized by effectively having a thin "skin" layer supported atop a highly porous and much thicker substrate region of the membrane.

2.1 MEMBRANE MATERIALS

The selection of membranes offered by the various suppliers in the business may appear to be confusing since many materials may be used to make membranes, and they are provided under an array of trade names. In reality, relatively few materials are actually used in quantity, and only a few basic membrane types form the bulk of the membranes being sold and used.

2.1.1 INTEGRAL MEMBANE MATERIALS

Cellulose acetate (CA) is the “original” membrane and is used for RO, NF and UF applications. The material has a number of limitations, mostly with respect to limited pH tolerance and temperature. The main advantage of CA is its low price, it’s ability to tolerate high levels of chlorine in the feed water (thus avoiding biological fouling issues), and the fact that it has a smooth, hydrophilic surface which makes it less prone to fouling.

Polyamide (PA) as the alternative RO membrane material used in this film composite RO membrane as discussed below under composite materials.

Polysulfone (PSO) in a number of varieties has been used for UF and MF membrane since 1975. PSO’s main advantage is its exceptional temperature and pH resistance. As a rule, PSO membranes do not tolerate oil, grease, fat and polar solvents.

Polyvinylidenedifluoride (PVDF) is a traditional membrane material and is increasingly used as it has a high resistance to hydrocarbons and oxidizing environments.

Polypropylene (PP) is a pure polymer membrane used in the manufacture of UF and MF membranes. Polypropylene has a low resistance to oxidizing agents.

2.1.2 COMPOSITE MATERIALS

Also called thin-film composite membranes, they appear under various acronyms such as TFC and TFM, and were made to replace cellulose acetate RO membranes. The main advantage is the combination of relatively high flux and very high salt rejection, 99.5% NaCl rejection commonly achieved with composite RO membranes. They also have good temperature and pH resistance, but do not tolerate oxidizing environments. Composite membranes are made in two-layer and three-layer designs, the precise composition of which is proprietary. Generally speaking, a thin-film composite membrane consists of a PSO membrane as support for the very thin skin layer of polyamide which is polymerized in situ on the PSO UF membrane. The three layer design has two thin film membranes on top of the PSO support membrane.

2.2 MEMBRANE GEOMETRICS

Spiral wound module: Consists of consecutive layers of membrane and support material rolled up around a tube. This creates a very large membrane surface area in a very compact space. Spiral wound systems are thus less expensive than other systems. However, the relatively constrained / tight feed spacer arrangement makes them more sensitive to particulate fouling.

Tubular membrane: The feed solution flows through the membrane core and the permeate is collected in the tubular housing. Generally used for viscous or feed solutions with high suspended solids. System is not very compact compared to an equivalent spiral system and has a high cost per unit area installed.

Hollow fibre membrane: The modules contain several small (0.3 to 1.2mm diameter) fibres. The fibres can be either submerged directly in the feed solution or housed in a cartridge. Typically, the feed solution flows from the "outside-in" and the permeate collected in the hollow fibre.

Flat Sheet: Flat sheet membranes are typically used for wastewater applications where the feed solution has high suspended solids. The flat sheet has a membrane surface on each side and a permeate carrier sandwiched between. The trans-membrane pressure is generated by the differential head between the water level in the membrane tank and the level in the permeate water tank.

2.3 MODULE CONFIGURATIONS

Pressurized system or pressure-vessel configuration: TMP (transmembrane pressure) is generated in the feed by a pump, while the permeate stays at atmospheric pressure. Pressure-vessels are generally standardized, allowing the design of membrane systems to proceed independently of the characteristics of specific membrane elements.

Immersed system: Membranes are suspended in basins containing the feed and open to the atmosphere. Pressure on the influent side is limited to the pressure provided by the feed column. TMP is generated by a pump that develops suction on the permeate side. Ultrafiltration, like other filtration methods can be run as a continuous or batch process.

2.3.1 MICRO FILTRATION

Increasingly used in drinking water treatment, it effectively removes major pathogens and contaminants such as *Giardia lamblia* cysts, *Cryptosporidium* oocysts, and bacteria. For this application the filter has to be rated for 0.2 µm or less. For mineral and drinking water bottlers, the most commonly used format is pleated cartridges usually made from polyethersulfone (PES) media. This media is asymmetric with larger pores being on the outside and smaller pores being on the inside of the filter media.

Microfiltration membranes were first introduced to the municipal water treatment market in 1987 and applied primarily to waters that were relatively easy to treat, such as clear source waters that were susceptible to microbial contamination. Low pressure membranes were selected to remove turbidity spikes and pathogens without chemical conditioning. As low pressure membranes increased in acceptance and popularity, users began to apply the technology to more difficult waters which contained more solids and higher levels of dissolved organic compounds. Some of these waters required chemical pre-treatment.

2.3.2 ULTRAFILTRATION

Ultrafiltration (**UF**) is a variety of membrane filtration in which hydrostatic pressure forces a liquid against a semipermeable membrane. Suspended solids and solutes of high molecular weight are retained, while water and low molecular weight solutes pass through the membrane. This separation process is used in industry and research for purifying and concentrating macromolecular (10^3 - 10^6 Da) solutions, especially protein solutions. Ultrafiltration is not fundamentally different from microfiltration or nanofiltration, except in terms of the size of the molecules it retains.

2.3.3 NANO FILTRATION

Nanofiltration (NF) is a cross-flow filtration technology which ranges somewhere between ultrafiltration (UF) and reverse osmosis (RO). The nominal pore size of the membrane is typically about 1 nanometre. Nanofilter membranes are typically rated by molecular weight cut-off (MWCO) rather than nominal pore size. The MWCO is typically less than 1000 atomic mass units (daltons). The transmembrane pressure required is lower than that used for RO, reducing the operating cost significantly. However, NF membranes are still subject to scaling and fouling and often modifiers such as anti-scalants are required for use.

2.3.4 REVERSE OSMOSIS

The process of osmosis through semi-permeable membranes was first observed in the 1700's. For the following 200 years, osmosis was only a phenomenon observed in the laboratory. In 1949, the University of California at Los Angeles (UCLA) first investigated desalination of seawater using semipermeable membranes. Researchers successfully produced fresh water from seawater in the mid-1950s, but the flux was too low to be commercially viable. By the year 2000, about 15,000 desalination plants were in operation or in the planning stages worldwide.

Osmosis is a natural process. When two liquids of different concentration are separated by a semi permeable membrane, the fluid has a tendency to move from low to high solute concentrations for chemical potential equilibrium.

By contrast, reverse osmosis is the process of forcing a solvent from a region of high solute concentration through a semipermeable membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure. The largest and most important application of reverse osmosis is to the separation of pure water from seawater and brackish waters. Seawater or brackish water is pressurized against one surface of the membrane, causing transport of salt-depleted water across the membrane and emergence of potable drinking water from the low-pressure side.

To overcome the natural osmotic pressure, a higher pressure is exerted on the high concentration side of the membrane, usually 5–15 bar for brackish water and 40–80 bar for seawater (depending on the required recovery).

2.4 CASE STUDY 1 – RO PLANT FOR AUSTRALIAN DEFENCE FORCE

2.4.1 BACKGROUND

In 2010 the Australian Defense Force (ADF) procured two Reverse Osmosis Potable Water Supply plants for two training camps in the Shoalwater Bay Training Area. The Plants were designed and installed to meet the Australian Drinking Water Guidelines based on a raw water quality as outlined in Table 2.

Table 2: Original and Revised Design Criteria

		Original Design Criteria	Revised Design Criteria
Fe	mg/l	0.2 combined	1.4
Mn	mg/l		0.062
TOC	mg/l	3	16
Turbidity	NTU	0.5	39
Colour	Hazen	5	200

The plant installed comprised a micron filter, pre-chlorination to oxidise iron and manganese, two pressure filters to remove the oxidised iron and manganese followed by sodium metabisulphite and antiscalent before being fed into the RO membrane plant. The RO permeate was then dosed with sodium hydroxide followed by calcium chloride prior to being fed into the treated water reservoir. Water leaving the treated water reservoir is disinfected using UV prior to distribution.

2.4.2 PROBLEM DEFINITION

It soon became evident that the raw water quality provided as the basis of design was inadequate and likely to be due historical data collated during the extended period of drought in Queensland from the late 1990's to the late 2000's. Soon after the plants were commissioned the raw water quality deteriorated and the plant throughput and treated water quality failed to meet the ADWG. In particular, the levels of iron and manganese (inorganic contaminants) were significantly higher than the original design criteria, as were turbidity and organic contaminants (TOC and Colour).

This resulted in the following operating issues:

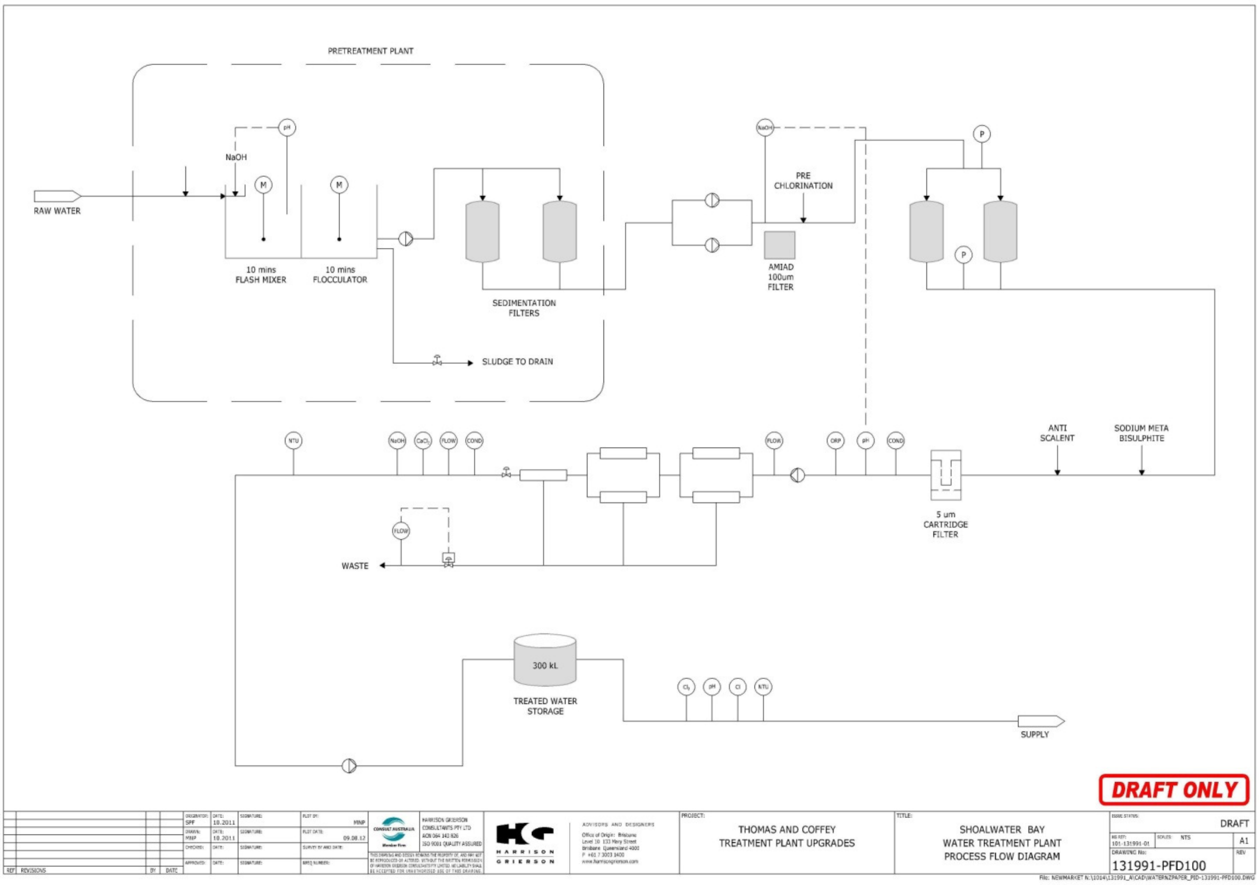
- High Iron levels blinding the membranes, evident by the high levels of iron and manganese in the dirty CIP wastewater.
- High operating pressures in the membranes skid (occasionally up to 13 bar) and in particular a high pressure drop on all membrane stages which are not reduced following citric acid cleans, indicating excessive organic fouling.
- Operations staff having to operate the plants bypassing the RO plant to keep up with demand.

2.4.3 SOLUTION

A pre-treatment plant was subsequently installed upstream of the original plant to cater for the revised raw water quality data and Harrison Grierson was commissioned to undertake a process audit and recommend further process improvements and optimisations. The resulting pre-treatment plant comprised:

- Coagulation and flocculation in a dedicated flocculation tank.
- Clarification by tube settler.
- Filtration by duty – duty pressure filters to remove residual solids.

Figure 1: Upgraded Brackish Water RO Plant Flow Diagram



The pre-treated water then flowed into the existing plant that comprised:

- pH correction and chlorination to oxidise iron and manganese.
- Filtration by duty – duty PTI pressure filters to remove iron and manganese.
- Reverse Osmosis filtration.
- pH correction and calcium chloride dosing.
- UV disinfection.

Photograph 1: Primary Filters

Photograph 2: Iron and Manganese Filters

Photograph 3: Skid Mounted RO Plant

The resulting plant was well engineered, easy to operate and meets the ADWG. In addition, each of the key process units is a compact, stand-alone package plant. As such the plant could have been supplied as a mobile plant. Whilst this wasn't a client requirement at the time, it does pose the question of what a purpose built mobile package plants are currently available.

Case studies 2 and 3 provide examples of such commercially available plants.

2.5 CASE STUDY 2 – BRACKISH WATER RO PLANT

2.5.1 BACKGROUND

In late 2010, an Australian Mining company approached GE to assess the availability and options for using the mobile water treatment equipment fleet to supplement production from the existing towns water treatment plant in order to meet the rapidly increasing demand from the township.

2.5.2 PROBLEM DEFINITION

There were a number of issues associated with the current situation:

The existing ion exchange softening plant was >30 years old, and was nearing the end of its useful life.

The mobile requirement was a temporary solution to add 2.5 MLD of supplemental capacity to meet the increasing demands for towns water as the Australian mining boom has swelled the population considerably in the space of a few months.

The feed water quality varied considerably depending on the bores that it was being drawn from (See Table 3).

All bores had relatively high (for Australia) silica levels which limited recoveries for membrane systems.

Table 3: Feed Water Quality

Item	Scale	Min Value	Max Value	Average
pH		6.8	8.5	8.2
Conductivity	uS/cm	600	2,400	1,800
TDS	mg/l	450	1,800	1,400
TH	Mg/l CaCO3	180	700	550
SiO2	mg/l	15	75	65

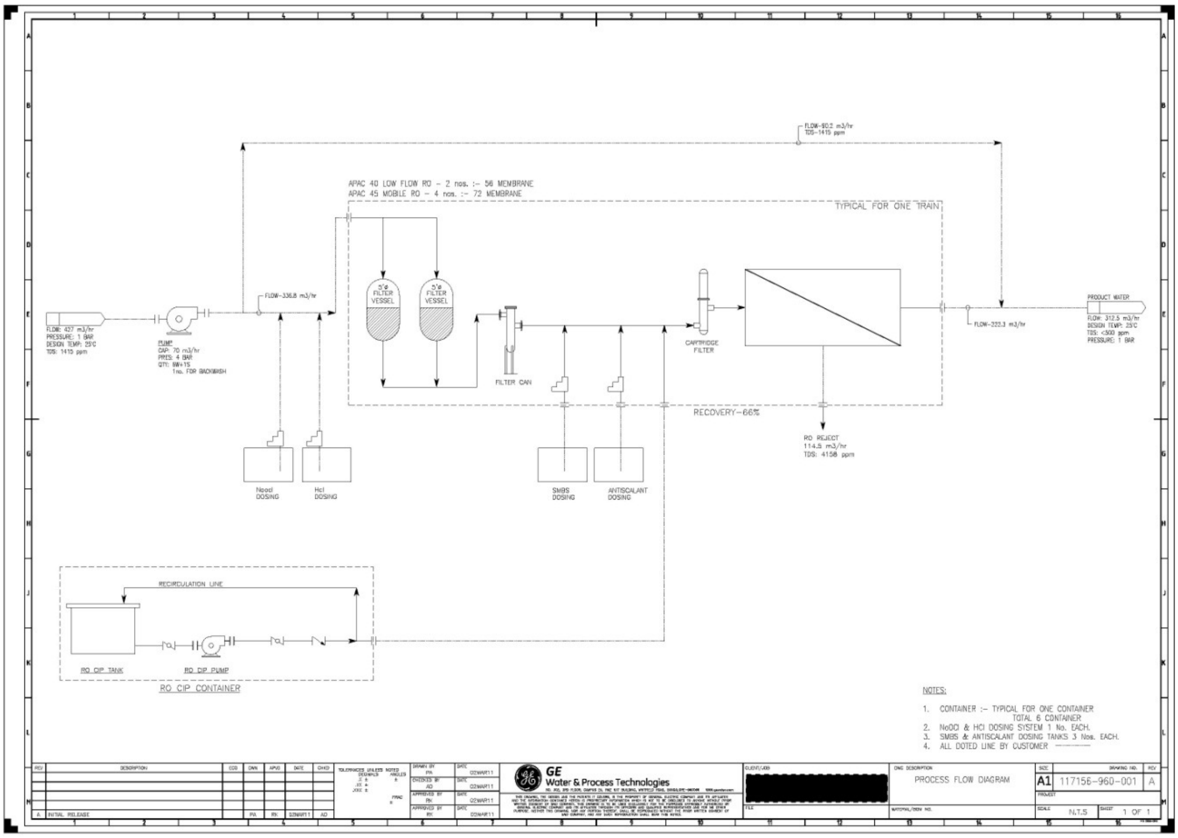
As discussions progressed, the customer decided that it would actually be best if the mobile equipment would act as a temporary replacement for the entire existing water treatment plant. This would enable the old plant to be demolished, and a new plant to be built on the same land. Thus the scope of the project increased, and it also meant that the temporary plant had to be located outside the existing plant boundary, to allow for safe demolition of the old plant, and construction of the new fixed plant. Unfortunately this limited the space available for siting the temporary plant, and the customer also wanted to have the capability to expand the plant in the future.

2.5.3 SOLUTION

The revised scope of works was for the system to make 7.5 MLD of potable quality water for the township. GE initially designed and provided a system comprising six containerized filtration/Reverse Osmosis systems, along with ancillary equipment comprising forwarding pump skids, chemical storage and dosing equipment and RO cleaning containers. Each Filter/RO unit was capable of producing 1 MLD, operating at 67% recovery.

As the permeate quality of the RO permeate would be much better than the requirement of <500ppm TDS, along with a suppressed pH, and exceptionally low hardness, after extensive modeling it was decided that to achieve a balanced product water supply, it would be best to blend some of the feed water with the permeate water in order to achieve the target TDS and pH. This was achieved by adding a controlled blending valve and bypass line into the system, linked to the site PLC.

Figure 2: System Process Flow Diagram



By using containerized equipment, within the limited space constraint, the design allowed for future stacking of additional units to enable expansion of the plant.

2.5.4 OPERATIONAL RESULTS

Five of the units were to be operational at any one time, with one (rotated) kept on standby just in case, producing 5 MLD, with the bypass blending line making up the 2.5 MLD shortfall. All units were controlled via tank level controls, with staggered start/stop triggers.

As soon as the plant was installed and commissioned, the demand from the town increased to levels higher than expected, or even previously measured, and so all six RO's are regularly put into service to produce >9MLD. The permeate quality from the RO units is consistently <50 uS/cm, and the blended product water quality remains within the drinking water parameters set by the customer. The RO systems continue to provide reliable service, with very little operator input.

After consultation with the local water authority, and once the Filter/RO units had been operating for a while, it was decided that the blend water should also undergo treatment. In early 2012 a containerized dual pass activated carbon filtration system was added to the bypass line, which has been operating without trouble ever since.

The customer is looking at adding two more RO units in the very near future to cover the increased water demand from the town.

Photograph 4: Mobile RO Containers On Site

2.5.5 KEY LEARNINGS

It was important for the customer and GE, that the local water authority was closely involved in all aspects of the design, operation and sign-off of the system. The LWA operates their own fixed RO systems elsewhere in the state, was able to provide experience and was best placed to advise on approvals, and monitor any customer feedback when the old water treatment plant was decommissioned, and the 'new' water came on line.

2.6 CASE STUDY 3 – 2.5MLD MOBILE ULTRAFILTRATION PLANT

2.6.1 BACKGROUND

A local water authority needed to overhaul a >30 year old single train clarifier and sand filter system that was the sole source of water for a small rural township in Eastern Australia.

2.6.2 PROBLEM DEFINITION

While the rural township in question was reasonably small, the local water distribution area included a large abattoir, that wouldn't be able to shut down for the three or so months that the upgrade work would require, so the required flow rate was 2 MLD. The site of the existing water treatment plant had limited space available, and was built on the side of a hill.

Table 4: Feed Water Quality

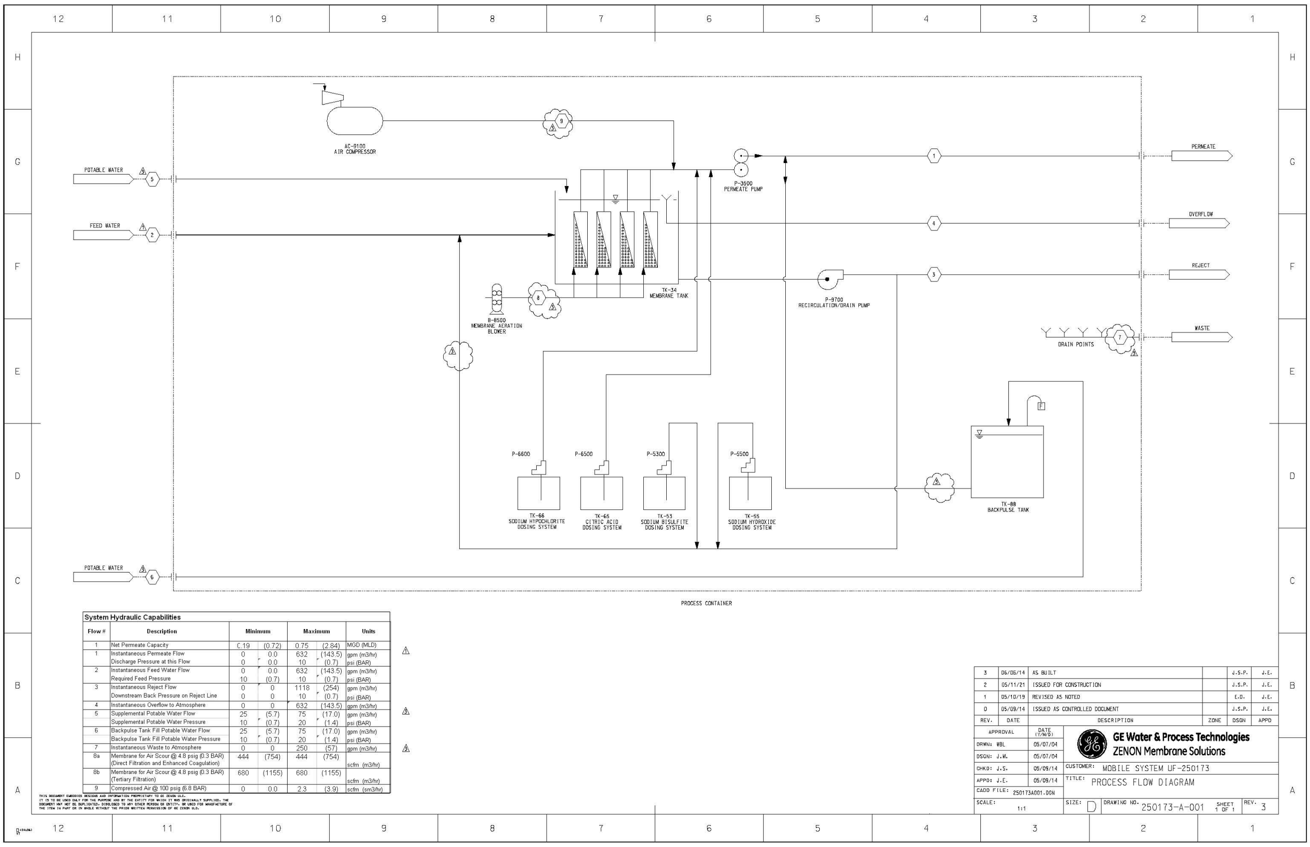
Item	Scale	Min Value	Max Value	Average
pH		7.1	7.8	7.6
Turbidity	NTU	5.1	31.0	8.3
Colour	True	120	250	130
Mn	mg/l	0.00	0.26	0.09

The feed water source was from the local river, and had the properties shown in Table 4 above.

2.6.3 SOLUTION

GE provided a 2.5MLD containerized submerged UF plant (ZW500 membranes), which included all of the chemical systems and controls required to operate with minimal operator intervention. The local water authority laid down a 13m x 3m concrete pad for the container to sit on, and hooked up the power and pipe work to their existing facilities.

Figure 3: Mobile UF Process Flow Diagram



As can be seen in Figure 2. the containerised unit contained all of the ancillary components required to provide full filtered towns water. The feed water was fed into a stainless steel tank containing four ZW500 membrane cassettes. A blower provided the continuous air scouring required on the outside of the membranes, while the permeate pump provided both the suction, and (in reverse) the back-pulse for the UF system. Chemical dosing systems included chlorination, CIP and pH correction capabilities. An in-built storage tank provided permeate for the back-pulse and CIP flows.

2.1.3.4 Operational Results

Since the unit was self-contained, the local water authority operated the unit (topping up chemical tanks, monitoring quality), while GE provided remote monitoring and a local (2 hr call out) engineer to assist for more complicated tasks, such as enhanced cleanings.

The unit ran successfully, providing consistent quality of filtered water for more than 6 months, while the existing sand filtration and clarification system was upgraded. While the unit was on site, the customer also took the opportunity to upgrade the chlorine dosing system as well.

Photograph 5: Mobile UF Container on Site

2.6.4 KEY LEARNINGS

While concrete slabs are not required for installing Mobile units, as they are capable of deployment on any hard standing, they do enable quick redeployment in case of future requirements.

3 CONCLUSIONS

Membrane technology is compact, robust and mature. The number of installations and applications are increasing. With a clear understanding of likely applications, a mobile membrane plant can be designed to treat a range of applications and raw water qualities.

However, it cannot be overstated enough, that the most important aspect of trouble-free membrane system operation is in making sure that the pretreatment process is suitable and robust enough to provide consistent quality water to the membrane.

There are a wide range of compact pretreatment technologies that are readily available to ensure sufficient and appropriate pre-treatment prior to MF, UF or RO membrane filtration. These pre-treatment technologies include tube and lamella settlers and high rate filters (installed with proprietary filtration media).

In addition, mobile equipment is different to the majority of (fixed) capital plants that are installed. Capital plants are typically designed specifically for the feed water, to have maximum recovery, and lowest price (to win the contract). Because Mobile plants will be utilized on a variety of differing water supplies over the units' life, and reliability is an imperative (breakdowns of capital plants form the majority of the needs), they are typically over-engineered to be robust, flexible, and reliable, in order to meet the market requirements.

Thus the challenge to the designer is develop a design that:

1. Is flexible in terms of application and raw water quality, using where possible standard and robust existing technologies

2. Is compact and can transported on standard 20' or 40' containers. Longer containers may be used but these may only be transported on selected routes, thus limiting potential opportunities.

3. Is complete with all necessary ancillary equipment such as chemical cleaning tanks and pumps, backwash tanks and of course all necessary equipment to cater for any waste streams generated.

4. Is modular, such that containers with the pre-treatment facilities can be easily connected to subsequent process trains and ultimately the membrane plant

5. Is affordable. With flexibility comes cost.

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