Thomas Peters[1]

[1] Dr.-Ing. Peters Consulting for Membrane Technology and Environmental Engineering, Neuss, Germany.

Review

Membrane Technology for Water Treatment

Membrane processes have become very important tools in water management and water related environmental engineering, because their efficiency has been proven from a technical and economical, as well as an ecological, point of view. This situation is partially based on results obtained during the operation of reverse osmosis systems that were developed in the early days of this technology for the desalination of seawater. Details regarding the theoretical background of these pressure driven membrane processes, examples of their application in water treatment, limiting factors, operational data and results for the purification efficiency are considered as the basis for the discussion of decision-supporting criteria for the selection of these technologies for possible applications, and as basis for the evaluation of future developments.

Keywords: Membrane processes, Ultrafiltration, Wastewater purification

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1 Introduction

Membrane processes including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO) have become important tools in water management, water related environmental engineering and industrial production, because their efficiency has been proven from a technical and economical, as well as an ecological, point of view, for some time now. This is partially based on results obtained during the operation of reverse osmosis systems that were developed in the early days of this technology for the desalination of seawater, with this process being one of the most important milestones in the history of membrane technology resulting in a patent being granted for the first spiral-wound-element in 1964 [1].

Membrane processes are used today for many different purposes, but mainly to overcome water scarcity and to prevent water pollution, whereby the choice of process type to be installed as a main step or in combination with other technologies depends on the type of components or contaminants, respectively, to be separated from the water to be treated, and on the quality requirements imposed for the water produced. Therefore, in the present case and due to the multifunctional use of membrane technology, the term *water treatment* is seen to comprise both the areas of conventional water management that are focused and loosely based on the cluster topics of *water of drinking water quality* and *municipal and industrial wastewater.*

Correspondence: Dr.-Ing. Th. Peters (dr.peters.consulting@t-online.de), Dr.-Ing. Peters Consulting for Membrane Technology and Environmental Engineering, Broichstr. 91, D-41462 Neuss, Germany.

In the last two decades, important innovations have been developed that have contributed to the realization of a great variety of membrane-based solutions and industrial processes. It can be concluded that after the pioneering time and introduction phase for these technologies in water treatment, it is now possible to design plants with a very wide range of production capacities and such plants are seen to operate with incredible reliability [2, 3].

In the case of desalination of seawater with reverse osmosis in order to produce drinking water, a cost of less than €1 per m^3 of water produced in plants over 50 000 m^3/day, and installations with a drinking water production capacity of 200 000 m^3 per day and more are now commonplace [4]. In the case of wastewater treatment, for example, the long term operational results show that the limit values imposed by legislation can be achieved with high reliability due to the barrier-function of the membranes [5–8]. The latter term, in turn, is based on the reliable and well-defined pore diameters of modern membranes, and/or, the functional principles of the membrane process itself.

2 Strategies in Water Management

In many regions worldwide, due to large population increases, it is no longer possible to satisfy the growing water demand by conventional methods of water procurement and processing [9]. Therefore, in addition to a more conscientious use of natural water resources, an increased utilization of advanced separation techniques such as membrane technology is called for, based on three main strategies, which are summarized in Fig. 1, and outlined below.

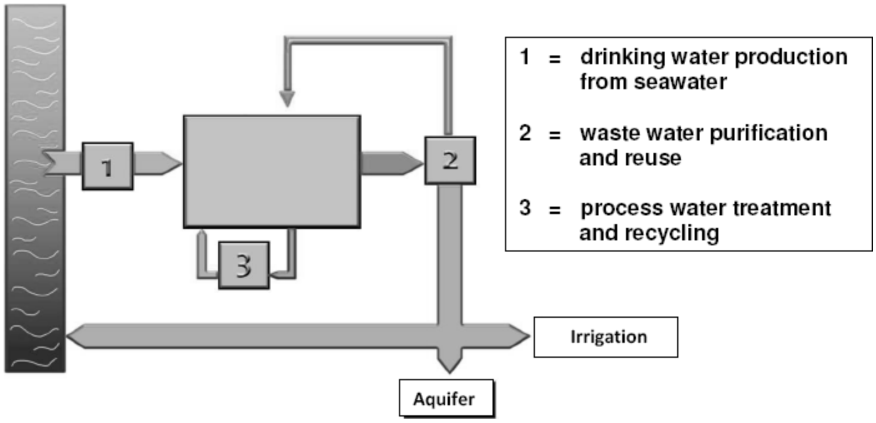

Figure 1. Solutions for the prevention of water shortages and protection of water resources [4].

2.1 Production

This approach is based on the production of potable water from saline and polluted waters in order to increase the amount of good quality water available in addition to that sourced from natural water resources. Some examples are:
– Desalination of seawater or brackish water (reverse osmosis);
– Separation of sulfate or reduction of the concentration of hard water forming components in drinking water (nanofiltration);
– Improved purification of river water (ultrafiltration), and
– Disinfection of water from dams and reservoirs (ultrafiltration).

2.2 Reuse

This approach is founded on the principles of the improved purification of wastewater in order to increase the exploitation potential or to reduce the consumption of potable water, respectively, by recycling or reuse of the purified water. Some examples include:
– The achievement of purified effluent from sewage treatment plants by implementation of membrane bioreactors as part of the treatment process, or use of membranes as an end-of-pipe treatment step for sanitation, and utilization of the filtrate for irrigation purposes (ultrafiltration);
– Purification of grey water in hotels and use for toilet flushing and irrigation (ultrafiltration);
– Purification of filter backwash water in swimming pools for use as bathing water (low pressure reverse osmosis);
– Purification of filter backwash water in water works to increase the production of potable water (ultrafiltration);
– Purification of grey water on ships and use as technical-grade water (ultrafiltration), and
– Purification of pretreated industrial wastewater for recycling in a semi-closed loop (low pressure reverse osmosis, nanofiltration, and ultrafiltration).

2.3 Protection

This approach is based on the prevention of further contamination of water resources by improved purification of wastewater and contaminated water. Some examples are:
– Purification of landfill leachate and controlled infiltration of the retentate into the landfill body in order to enhance the production of landfill gas, and thus, contribute to an accelerated biodegradation process (reverse osmosis and nanofiltration);
– Treatment of acid mine drainage (AMD, nanofiltration);
– Purification of animal waste products, e.g., pig slurry and digestate from biogas plants (ultrafiltration, nanofiltration, and reverse osmosis);
– Purification of the effluent from sewage treatment plants to reduce the contamination of receiving rivers (ultrafiltration), and
– Purification of black water on ships or in hotels to protect the environment (membrane bioreactor based on ultrafiltration).

The growing worldwide concern in recent years regarding environmental pollution, more stringent legal requirements concerning the quality of drinking water or bathing water, and the anticipation of tightened global waste discharge regulations have been a few of the driving forces for the increased acceptance and wider use of these technologies in water treatment processes [4]. Another aspect has been the increasing realization with regard processes relating to the rejection linked characteristics of the membranes allowing for the recovery of valuable components, e.g., from industrial wastewater, according to the concept *From Discharge to Reuse*. This concept also applies to the water itself after treatment or purification, since the awareness of the concept that *water has a value, not only a price* is heightened.

3 Membrane Processes

The membrane processes in use for water treatment are pressure driven separation processes, where the driving force is a pressure difference across the membrane. With these membranes, the water to be treated is separated into a stream of filtrate or permeate and a remaining quantity of retentate, also known as concentrate (see Fig. 2). The components contained in the feed water, which have been rejected by the membrane are accumulated in the retentate.

The membranes used in these processes can be considered as well-defined barriers. This allows for continuous and reproducible control of the quality of the filtrate or permeates, respectively, obtained with robust measuring instruments. At the same time the barrier-function of the membranes guarantees that a high quality filtrate or permeate is achieved, which

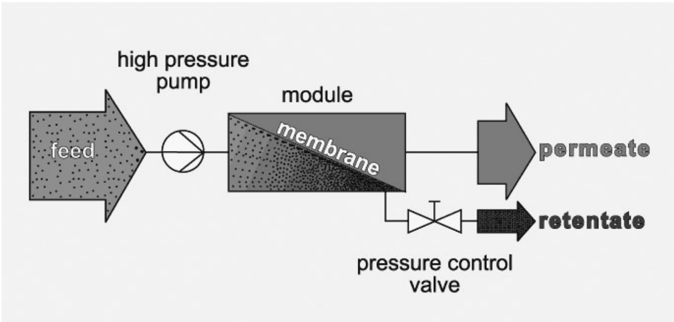

Figure 2. Flow diagram for reverse osmosis as an example of the functioning of pressure driven membrane processes.

is almost independent of changes in the concentration of components or contaminants in the feed.

Plants equipped with MF, UF, NF or RO membranes – if correctly designed, manufactured and operated – show a high operating stability, since the process is switch operated. The different modes of operation, e.g., start-up, normal operation, intermittent operation, flushing, cleaning, shutdown or emergency shutdown are initiated by pressing a corresponding switch or by a stored command. During operation, these commands are controlled by a PLC (Programmable Logic Controller). The start-up and shutdown require no special attention and can be realized in a few minutes.

The modular design of the systems is a basis for high flexibility against changes in the volume of water to be treated and results in a small carbon footprint for the plant itself. The compactness of these plants, short construction time, cleanliness, ease of use, as well as economic and long term operational reliability are further advantageous aspects. These features result from the intrinsic properties of the membranes and from their combination with an appropriate module configuration and plant design that must be strictly adapted to the needs of each specific application. The reasons for this selection are based on the capabilities of the processes and are discussed in detail in the following sections.

3.1 Microfiltration

Microfiltration is the membrane filtration process with the least restrictive membrane type. Its uses include, e.g., bacteria and pigment removal and elimination of other particulates with particle sizes in the submicron range. They are porous membranes with pore sizes in the range of ca. 0.1–1.0 µm (1 mm = 1000 µm), with an average pore size of 0.2 µm being the most common for commercial membranes. The operating pressure is up to 500 kPa (5 bar).

3.2 Ultrafiltration

Membranes for ultrafiltration can remove bacteria and viruses and can also separate macromolecules such as sugars and proteins, as well as colloidal silica and pyrogens. Typical molecular weight cut-off ranges vary from 5000–200 000 g/mol. The usual pore size is in the region of 0.05 µm. The operating pressure is up to 1000 kPa (10 bar).

3.3 Nanofiltration

The membranes used in nanofiltration operate on a solution diffusion principle, where monovalent ions diffuse through the membrane, rather than blocking ions from passing through the membrane because of pore size, as happens in microfiltration or ultrafiltration. Nanofiltration is useful, e.g., for color removal, sugar and dye removal or for removing THM precursors and hardness or sulfate from water supplies or wastewater sources such as acid mine drainage (AMD) [10]. The operating pressure is up to 5000 kPa (50 bar).

3.4 Reverse Osmosis

Reverse osmosis is operated with the tightest type of membrane available. The organic and inorganic molecules are separated from a feed solution by a solution diffusion process. Typically, reverse osmosis membranes are used to separate dissolved salts and ions with a molecular weight of less than 200 g/mol. The applications range from the production of ultrapure water for semiconductor and pharmaceutical use to the desalination of seawater for drinking water production and the purification of industrial wastewater, such as landfill leachate. The operating pressure is usually up to 7000 kPa (70 bar), and up to 15 000 kPa (150 bar) for high pressure reverse osmosis systems.

4 Fundamentals of Membrane Processes

4.1 Membranes and Modules

Artificial membranes are usually made by casting a plastic-like, semipermeable membrane barrier onto a backing material. The casting process and chemical formulations used determine the molecular weight cut-off or rejection of the membrane being produced. For both microfiltration and ultrafiltration membranes, which are usually described as asymmetric porous membranes, casting onto the backing material is the only step required. For nanofiltration and reverse osmosis, which are non-porous asymmetric membranes, the cast membrane must then be coated with a thin, high rejection layer to form a thin film composite membrane.

These casting and coating processes are highly sensitive and require experience and care to produce a consistent product. However, the fact that more than 40,000,000 m^3 of drinking water are produced from seawater per day with reverse osmosis actually proves the reliability of these types of membrane. Whereas polymers or mixtures of polymers are usually used to form the membranes, and/or, the thin film, for some applications, ceramic membranes with an overlayer of metal oxide or ceramic material are produced.

Membranes can be produced in flat sheet form, in tubular form, as capillary (mono-bore or multi-bore) or as hollow fiber membranes. These are then configured to form a membrane element and in the next step to generate a module, such as tubular (see Fig. 3), capillary or hollow fiber modules. With flat membranes, spiral wound elements (see Fig. 4) are manufactured, or formed into modules with an open channel design such as the spacer tube, cushion, plate and frame or disc tube module (see Fig. 5). In addition, ceramic membranes offer the possibility of forming multichannel membrane elements (see Fig. 6).

A module is defined as the smallest practical unit containing one or more membranes or membrane elements and supporting structures, such as end caps or other material required, so that the resulting unit can operate independently from the rest of the plant, if required.

Figure 3. Tubular membrane element (source: CUT).

One of the important criteria for the selection of a module type for a defined application is the membrane packing density, given in m^2/m^3. This defines the effective membrane area installed per volume of a module. Some examples of average values for different modules are ca. 10 000 m^2/m^3 for hollow fiber, ca. 1000 m^2/m^3 for spiral wound, ca. 200–400 m^2/m^3 for disc tube and ca. 40 m^2/m^3 for tubular modules.

The packing density is the main indicator for the degree of pretreatment necessary for the different modules in order to achieve a safe and trouble-free, long-term operation. The desalination of pure seawater with a low silt density index, achievable with a high degree of pretreatment, is possible with modules possessing a high membrane packing density.

Wastewater usually requires open channel modules, characterized by low values for the membrane packing density with a low degree of pretreatment. Some reasons for this are long time accumulation effects induced by particles in the sub-micron range and the possible blocking of the spacer in the feed water channel of the modules with a high packing density resulting from scaling, fouling and biofouling.

One application with increasing international importance is the use of membranes in combination with activated sludge processes in membrane bioreactors (MBR) for the treatment of municipal wastewater and industrial wastewater [8]. Depending on the application, the units are designed with the modules installed externally (see Fig. 7, [11]) or with sub-

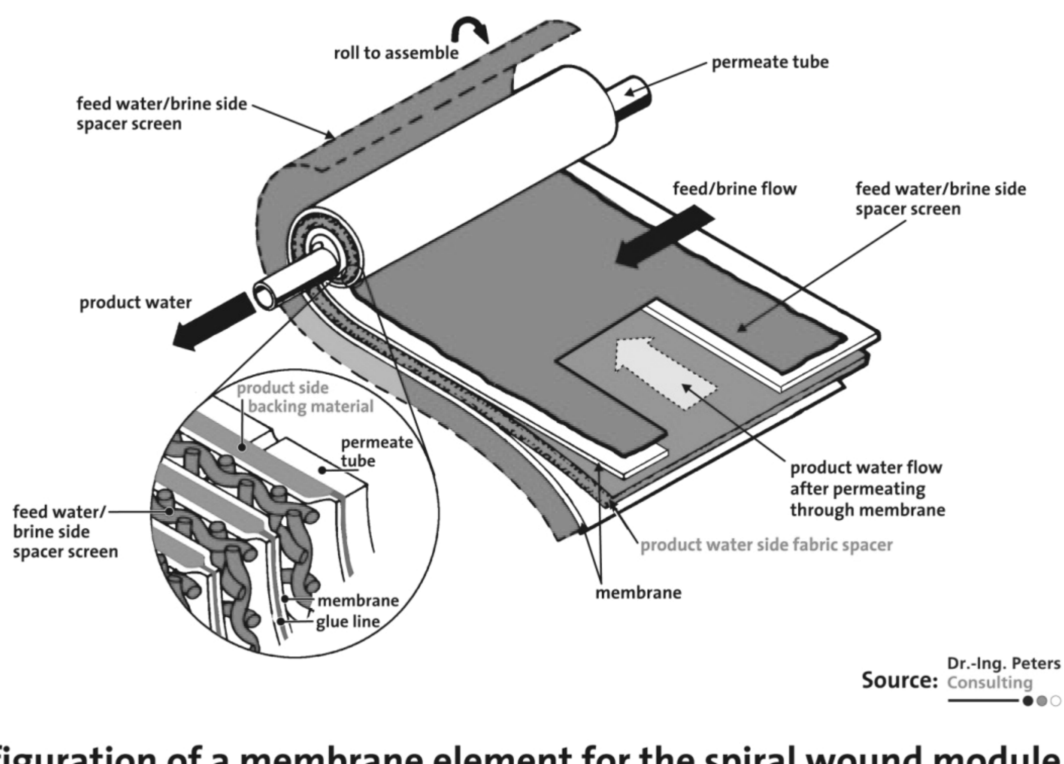

Figure 4. Spiral wound element [4].

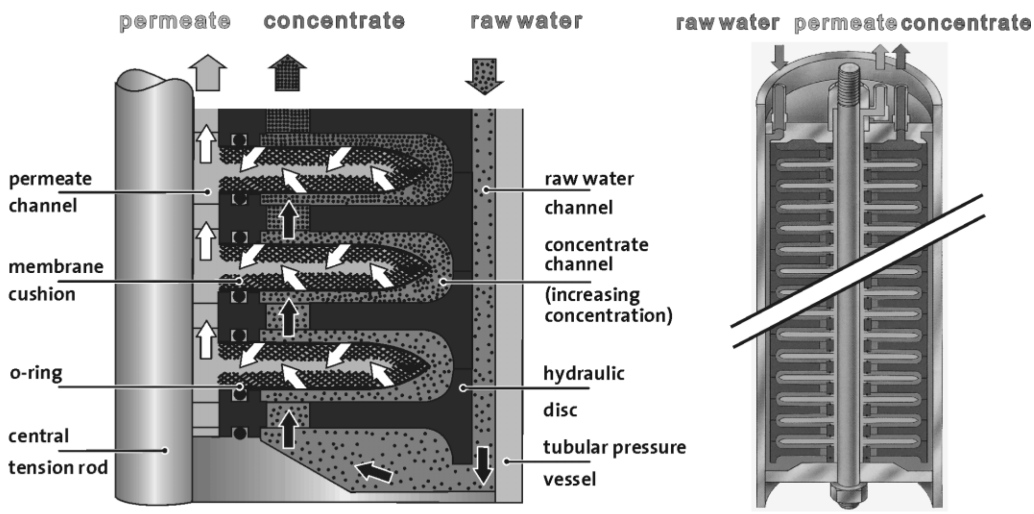

Figure 5. Disc tube module (source: ROCHEM).

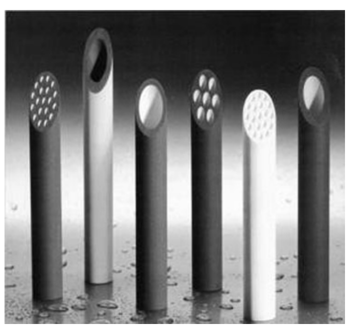

Figure 6. Ceramic membrane elements (source: Atech).

Figure 7. Membrane bioreactor consisting of an external module with UF membranes for wastewater treatment on Mega Yachts (see [11]).

merged modules (see Fig. 8, [8]), and operated with, e.g., a slight vacuum of 5–20 kPa (50–200 mbar).

This area of application is another good example demonstrating the possibility of adapting membrane technology to almost any area due to the modular design of the units. Whereas larger sized membrane bioreactors have been installed for the treatment of, e.g., ca. 48 000 m^3 of municipal wastewater per day [8], incredibly small units can be operated successfully in households of 4 residents with a range of 25–50 L/h. Other special cassette modules are used (Fig. 9), which can be adapted to a *plug and play* unit for easy installation in a three chamber unit for water reuse in remote areas, based on the concept of low maintenance, decentralized wastewater treatment and sanitation [12].

4.2 Membrane Performance Parameter

Cross-flow is the usual operating method in membrane filtration processes, in which the water to be treated is pumped in a direction parallel to the membrane surface. Due to the flowing liquid, hydrodynamic shear stresses are formed that control the formation of the fouling layer on the membrane surface. This helps to stabilize the filtrate flux, or permeate flux respectively, through the membrane to a major degree.

The dead-end mode with low energy demand is usually applied for the treatment of water with a low content of particulate matter, e.g., water from dams or effluents from sewage

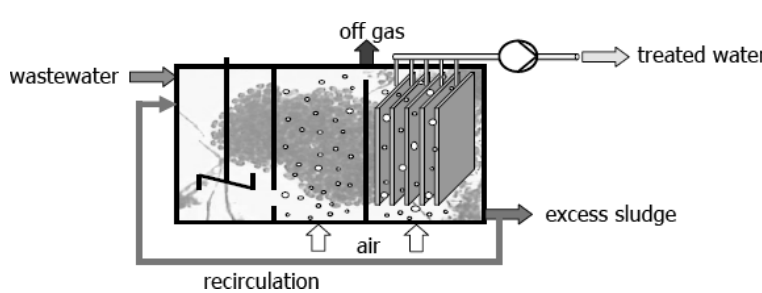

Figure 8. Schematic of a membrane bioreactor with submerged module [8].

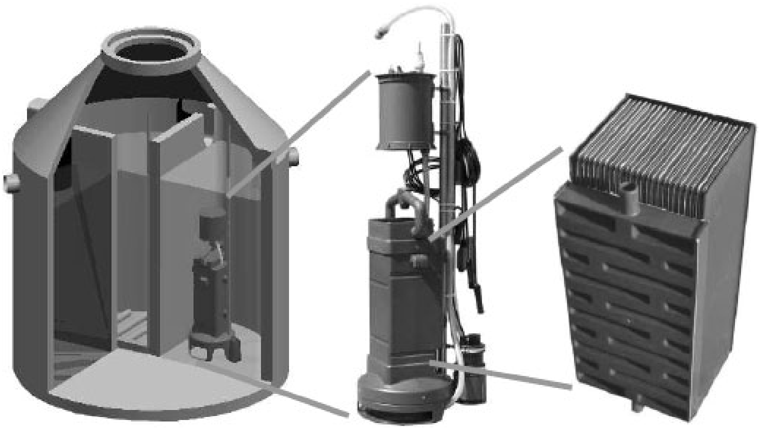

Figure 9. Cassette module with ultrafiltration membranes for decentralised water treatment in a 3-chamber-based small membrane bioreactor [12].

treatment plants. The combination with a small internal recirculation stream (*excess recirculation*) and an air bubble supported cyclical backwash can help to enhance the specific filtrate flux and avoid clogging of the membranes (see Fig. 10) [13].

As mentioned above, the driving force for ultrafiltration and microfiltration is the transmembrane pressure only, and the transport of components in these porous membranes is mainly based on convection. For nanofiltration and reverse osmosis, the transport of the dissolved components is based on diffusion. Therefore, nanofiltration membranes show very low rejection rates for monovalent ions, whereas bivalent ions and dissolved organic components with molecular weights above 200 g/mol (Dalton) are rejected to a higher degree, allowing for interesting and valuable separation applications in industry.

Since more and more purified water is produced as filtrate or permeate during operation, the concentration of the components originally contained in the feed water is increased in the membrane along the flow direction. Therefore, the concentration depends on the recovery rate, the ratio between the volume of permeate obtained and the initial feed volume pumped into a membrane system. If, for example, a recovery rate of 80 % is achieved, i.e., 80 % of the amount of feed water is produced as permeate, then a concentration factor of 5 is obtained for the components in the retentate (concentrate) leaving the plant.

The increased concentration of particulate or dissolved matter in the feed water may result in the deposition of biological material on the membrane surface, and/or, its pores, i.e., fouling, or the deposition of inorganic particles that are produced by crystallization or precipitation of dissolved components after reaching saturation, e.g., calcium carbonate or calcium sulfate, i.e., scaling. It is usually difficult to control biofouling since this is formed by a biofilm that increases with time. All of these depositions change the membrane performance in a negative manner and require different approaches in order to be reduced or avoided. However, apart from the cleaning strategies and corresponding cleaning agents available on the market, each application usually has to be investigated on a case-by-case basis to identify the most efficient procedure, due to the different parameters that can influence the operation of a membrane plant. These services are offered by specialized companies that have the required expertise necessary to achieve an optimized cleaning result [14].

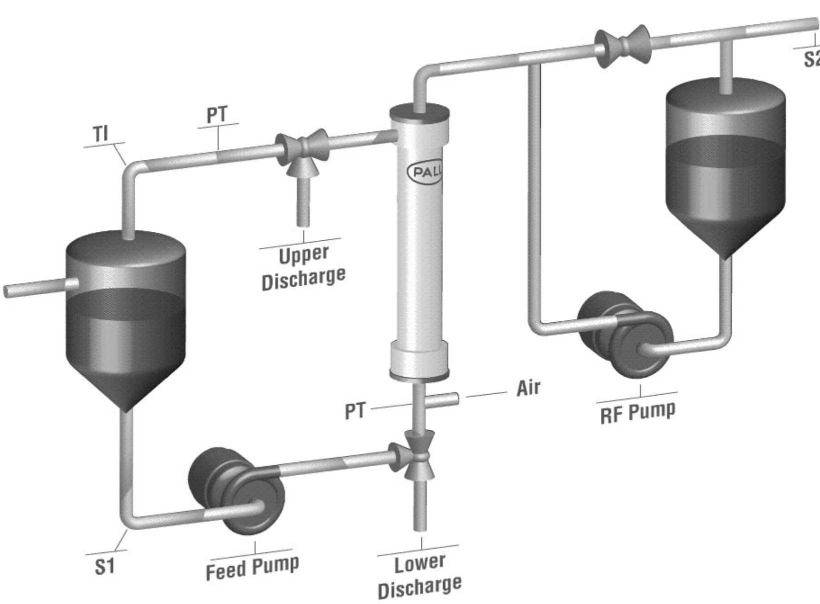

Figure 10. Operation of ultrafiltration with a combination of dead-end mode (100 % filtrate produced from 100 % feed water) and internal “excess recirculation”, e.g., 105 % fed to the module, whereby this additional 5 % of feed volume is re-circulated to the feed side [13].

4.3 Operational Cluster of Membrane Plants

While approved and well known technical solutions are usually available for the design and the manufacture of a membrane based unit, the pretreatment of the water to be processed, as well as the handling of the retentate have to be adapted case-by-case to the specific conditions at the construction site of a plant. These can differ over a wide range, since apart from the influences determining the raw water quality, details relating to the infrastructure or logistics are usually very different, and consequently, have to be considered during the design, construction and operation of each membrane plant.

This includes the systems for dosage and the handling of agents for pretreatment, agents needed during operation, and agents for the cleaning of membranes, and in addition, the treatment and discharge of the wastewater streams generated during these activities. A flow sheet has been developed for the specification and evaluation of the correlated interdependencies (see Fig. 11), that summarizes the main operational cluster of a membrane plant, here specified for a seawater desalination plant with reverse osmosis as an example. The term ICT refers to *Information and Communication Technology*, which is the basis for an efficient SCADA (Supervisory Control and Data Acquisition) System including remote control and data handling [15].

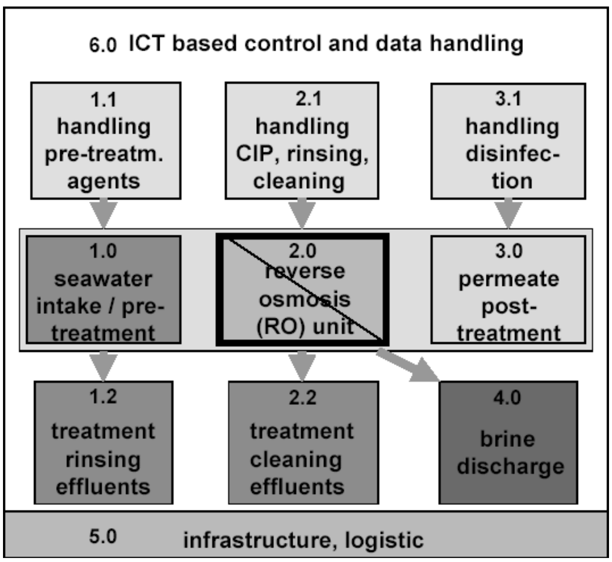

Figure 11. Operating cluster of a membrane plant for a process stream specification [15].

The data in Fig. 11 summarizes findings and experience resulting from many different activities in the field of membrane technology that in principle, can be transferred to almost any application of membrane processes in water or wastewater treatment, but in the present example, have focused on seawater desalination. It is important to consider precisely in the initial design, that the raw water intake, the pretreatment, the membrane stage and the post-treatment of the permeate, together form one operational unit, and are not – as is found in some cases – considered as individual stages, which can be connected under certain framework conditions that are not usually specifically stated.

It is also important to note that the wastewater generated in the pretreatment and the wastewater generated during membrane cleaning are treated separately and not mixed for discharge as has been usual practice in the past. Such an approach can be deduced from the graph in Fig. 11, as well as from the associated methodology. On one hand, the separate handling allows for recycling possibilities for certain partial streams, and on the other hand, an environmentally sustainable operation that avoids the contamination of the receiving water body is achieved.

5 Future Development of Membrane Technology

At present, important developments are taking place in industrial membrane applications focused on the integration of different membrane processes in thermal separation technologies and chemical or biological transformations. By bearing these in mind, better product quality, highly compact production plants and processes with improved efficiency, reduced energy consumption and sustainable, environmentally friendly operation can be achieved [2, 3].

The future development of membrane technology will be influenced by factors such as:

- The degree of purification of the fluid to be treated as expected from the customer or imposed by law, being driving forces for the development of solutions. In this case, these would be mainly ecological aspects such as increasing environmental pollution, stricter discharge regulations and avoidance of chemicals;
- A reduction in treatment costs because of increasing operational experience and longer membrane lifetime;
- The production of membranes adapted to specific applications;
- Increased efforts to reduce biofouling on the membrane surface;
- Reliable process monitoring;
- Reliable discharge control;
- Standard plant concepts with easy adaptation to each individual situation on site;
- Realization of *plug and play* concepts;
- Broader use of Build-Own-Operate or Build-Operate-Transfer agreements, and
- Integration of membrane technology in a total water management system based on *graduated quality requirements*.

6 Conclusions

Membrane technology is used successfully, and increasingly, for different purposes and for a wide range of applications within the area of treatment and purification of water and wastewater. This is based on features including compactness of the plants, short construction time, clean, easy, economical and long term reliable operation with high rejection rates for components or contaminants. This is mainly due to the barrier function of the membranes, but is especially based on the experience gained in the last decade and the improvements in material selection for the manufacturing of the membranes and the plants, as well as, the increasing optimization of operational aspects including capacity building and preventive maintenance.

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