Process Water Production from River Water by Ultrafiltration and Reverse Osmosis

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1. Abstract

The new process for process water production from river water is divided into three stages: prefiltration, ultrafiltration and reverse osmosis.

The latter technique has been state-of-the-art in the preparation of drinking water, boiler feed water and ultrapure water from conventionally pretreated raw water for many years. On the other hand, ultrafiltration is new to this sector and has only recently been used on the industrial scale. It is used as a single-stage process to purify drinking and process water as well as surface water as an alternative to conventional treatment processes (e.g. ozonization-precipitation-flocculation-coagulation-chlorination-gravel filtration).

Multistage, fairly complex processes are employed in the conventional pretreatment of river water. The use of different chemicals necessitates special safety measures and careful harmonization and control of water chemistry in view of the requirements of downstream reverse osmosis. By contrast, processes based on membrane technology enable a simply designed plant to be used with several advantages.

Axiva in cooperation with the water supply company for the Höchst Industrial Park have developed and successfully tested an efficient and cost-effective ultrafiltration process for river water in pilot-scale operation over several years. During this trial period low-energy systems based on different filtration concepts (cross-flow, dead-end), efficient hydrophilic membranes and a specific operating and backflushing technique specially designed for the application were employed. In this way reliable plant operation with high availability was obtained and suspended particles and microorganisms were removed from the river water (River Main) without any problem. The permeate quality was very high throughout the trial period (< 0.05 NTU) and met the requirements for feed water to the RO plant.

Stahlwerke Bremen, a major steel company, in cooperation with the Institute of Environmental Process Engineering of the University Bremen and Axiva are building a large-scale pilot plant for the treatment of water from the River Weser by the combination of direct ultrafiltration and reverse osmosis (total capacity 36 m³/h RO-permeate). The aim of this joint cooperative venture is to acquire operating experience with the pilot plant over an extended period. In three years' time the experience gained can be used in a full-scale plant replacing existing conventional plant technology to produce ultrapure water with the new, modern treatment method. The pilot plant is being started up in July 2000.

2. Introduction

In industrial processing water is used in numerous applications requiring likewise different qualities of water. Examples of different use are cooling water, water for rinsing and chemical production, boiler feed water, purified water, water for injection, just to mention a few of those. On a chemical site or within a factory commonly a central water production unit is providing the basic amount of water in several qualities.

These water supply units are using more and more surface water like river or reservoir water substituting ground or well water in the production of potable water or industrial process water. The reasons are increasing costs for ground water (taxes,...) and new available technologies enabling a quality and cost efficient (less O&M costs) treatment e.g. membrane filtration. 15 years ago reverse osmosis (RO) became state-of-the-art for the production of demineralised water (boiler feed or process water) from conventionally pretreated surface water. Recently direct ultrafiltration (UF) of those surface water without any pretreatment except a common screen filter has become a suited solution for direct production of pure water (e.g. potable water) or as an efficient pretreatment in combination with RO.

A conventional surface water treatment plant consists of a multi-step process applying screen-filtration, ozonisation, coagulation and flocculation, sedimentation, sand filtration, and usually disinfection as a last step. The use of ozone, flocculents, hydrogen peroxide, lime and chlorine requires special precautions for safety purposes. Each step of this process has to be controlled to get an optimal performance of the overall process, which results in a complex control system. As opposed to this, the UF membrane filtration process provides the following advantages:

- Very high pure water quality – practically independent of variations in raw water quality.
- The membrane plant is easier to automate owing to its simple design and offers greater flexibility owing to its modular construction (e.g. later extension of capacity)
- No chemicals are used apart from those for cleaning the membranes, i.e. substantially reduced residues and by-products.
- Because of the physical barrier of the UF membrane, the permeate (feed water from RO) is free from viruses and other microorganisms, which results in significantly less biofouling or recontamination in subsequent stages (e.g. RO).

While purification of reservoir water by the membrane process has been tried out on a pilot scale in many places, and in France, the Netherlands and the USA particularly has already been used industrially, the production of pure water directly from river water by membrane filtration is largely unknown. An important consideration that has so far prevented the use of low-energy systems for this purpose is the significantly poorer water quality as compared with reservoir water. In this respect the use of ultrafiltration for the direct treatment of river water was not economic in the past because the corresponding UF systems were too large, unreliable in operation or too energy-intensive.

In process development, the constantly changing river water composition and highly fluctuating demand requirement profile are the primary concerns, which together call for a strictly modular system structure.

In different piloting and engineering projects the use of an ultrafiltration plant as an alternative process for producing pure water (as a pretreatment method for reverse osmosis) from river water is being tested and realised at present. In the following the projects as well as process concepts (cross-flow, dead-end), piloting results and process engineering aspects are presented for two sites in Germany.

- River Main: Water supply of industrial site Höchst (InfraServ GmbH, Frankfurt)
- River Weser: Water supply for stainless steel industry (Stahlwerke Bremen GmbH)

3. River Main: Industrial Site Höchst (InfraServ Frankfurt)

At the Höchst Industrial Park, direct ultrafiltration - as a single-stage water purification process for river water -is being examined as an alternative to the multi-stage conventional treatment process. The studies are being carried out with two pilot plants that are based on different filtration concepts and operate with different membranes. Extensive test results show that ultrafiltration can be economically used, even for surface water imposing increased demands on filtration technology.

Some 90 % of the water supply to the Höchst Industrial Park is provided by treated river water from the River Main. In the existing process for pure water production, gravel-filtered Main water is first ozonized for the purpose of sterilization, then mixed with Fe^{3+} salts in the trickler and after flocculation and inline coagulation is chlorinated and again gravel-filtered (see process flow diagram in figure 1). Most of this pure water is used in place of drinking water as high-quality process water in the production plants. The remainder is fed into a reverse osmosis system (partial deionization) followed by multi-step ion exchangers (complete deionization) for the production of boiler feed water.

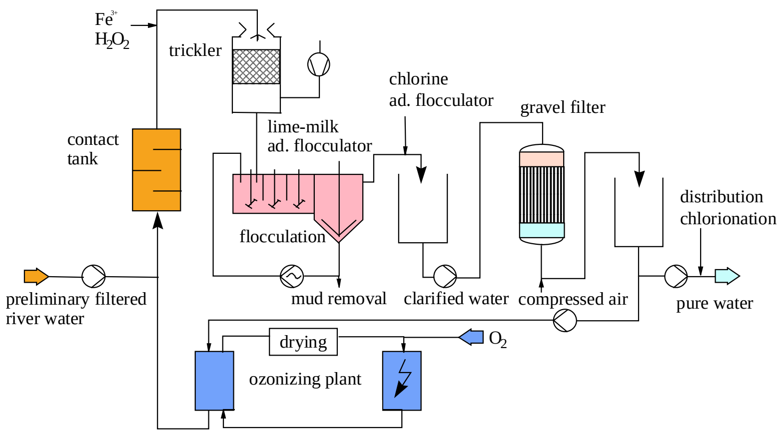

Figure 1: Flow diagram of pure water production (capacity max. 1200 m^3/h pure water)

At the Höchst Industrial Park, two pilot-scale plants are at present being operated to test river water treatment by ultrafiltration as an alternative to the multi-stage conventional process (see figure 2). The aim is to develop a reliable single-stage process that meets high quality requirements but also significantly reduces personnel costs in order to lower the specific pure water costs. These UF-plants differ essentially in their mode of operation (dead-end / cross-flow), the type of membrane used and capacity. Both systems operate with capillary modules and, depending on river water quality, work with gravel-filtered or rotary screen-filtered (filter fineness = 0.6 mm) Main water (= raw water).

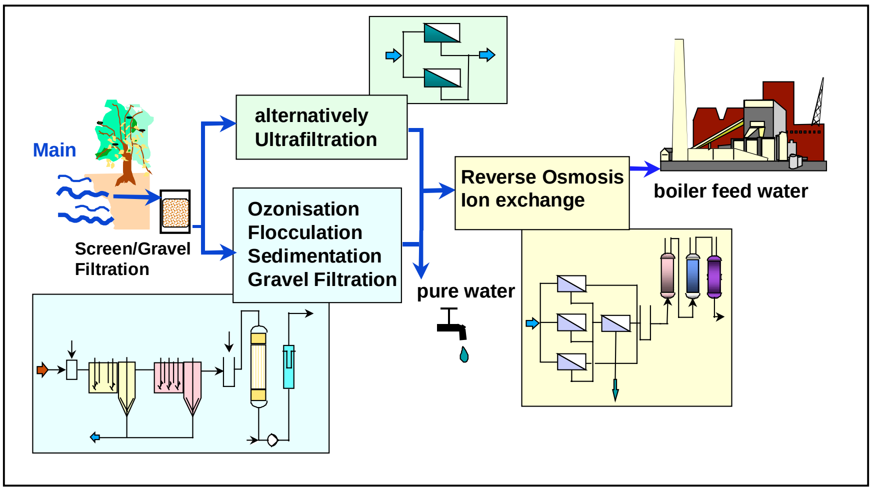

Figure 2: Scheme of the water supply Höchst Industrial Park

3.1 Cross-Flow UF

This filtration plant operates on the cross-flow principle with closed loop technology and permeate flow control. It consists of the following components: filtration unit, control unit and data logging system. A schematic diagram of this pilot plant is shown in figure 3.

The normal operation of the unit consists of filtration and backwashing or chemical backwashing, which take place in alternation.

During the filtration cycle, exactly the same quantity of raw water is fed through a preliminary filter into the closed loop, as of permeate and bleed leaving the pilot plant. With the aid of the cross-flow pump and reject pressure valve, the membrane cross-flow and feed pressure gradient for the UF module are adjusted. To prevent the concentration of retained water constituents becoming too high during the filtration process, part of the retained substance flow is bled off from the loop. The permeate is either passed into the permeate tank or leaves the system as product. At the end of the filtration cycle, backwashing takes place. This can be carried out either as conventional backwashing (permeate only) or chemical backwashing (permeate and backwashing chemical).

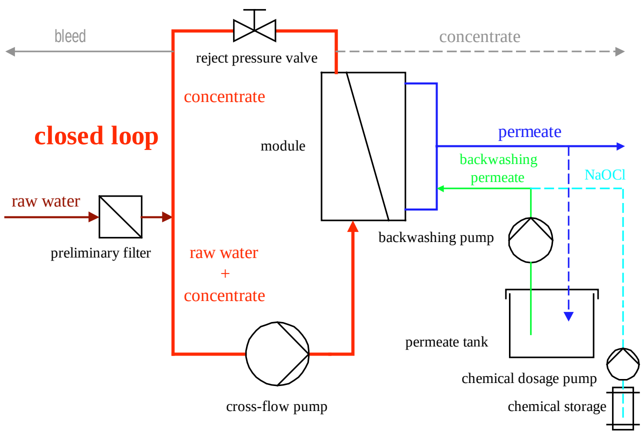

Figure 3: Schematic diagram of cross-flow UF

With the backwash pump, permeate is forced through the UF module in the reverse filtration direction at twice to three times the transmembrane pressure (TMP) and so removes the water constituents retained by the membrane. The concentrate thus produced is discharged as wastewater from the filtration unit.

The main component of the unit is the MOLPURE FW50-Technology, a 4-end module produced by Daicen, which is equipped with the FUC 1582 capillary membrane. The capillary inside diameter is 0.8 mm, the membrane consists of hydrophilic cellulose triacetate, has a double asymmetric structure and a nominal molecular weight cut-off (MWCO) of 150 kDa. The tests are carried out using a pilot-module (FS10-FS, membrane area 5,3 m²) with a hollow fibre geometry similar to those of the large scale module FW50.

A special feature of this cross-flow UF unit is the very low membrane cross-flow rate of 0.3 m/s, which significantly cuts energy consumption in comparison with the conventional cross-flow process (3 to 5 m/s cross-flow rate). Consequently the energy demand is very close to the dead-end UF. In addition, because of the structure of the membrane used, a TMP of only 0.5 bar is required, which again helps to reduce energy costs.

3.2 Dead-End UF

Like the cross-flow plant, the second pilot plant also consists of a filtration unit, control unit and data logging system. However, it operates on the dead-end filtration principle. A schematic diagram of the plant is shown in figure 4.

The dead-end pilot plant has the same operating modes as the cross-flow plant but with shorter filtration times (dead-end 15 min, cross-flow 45 min). Since no membrane-parallel cross-flow is produced in dead-end filtration, this system does not have a cross-flow unit with loop operation and bleed take-off. The preliminary filter has a mesh aperture of 200 µm.

The UF unit consists of two capillary modules arranged in series in one pressure housing. The two modules (type S-225-X PVC UFC M5 from X-Flow) are equipped with doubly asymmetrical capillary membranes made from hydrophilic polyethersulfone. With a capillary inside diameter of 0.8 mm, a 35 m² membrane surface area is available in each module. The nominal MWCO amounts to 150 to 200 kDa. The module design corresponds to the 8"-cartridge design of modules normally used in membrane technology (e.g. spiral wound modules).

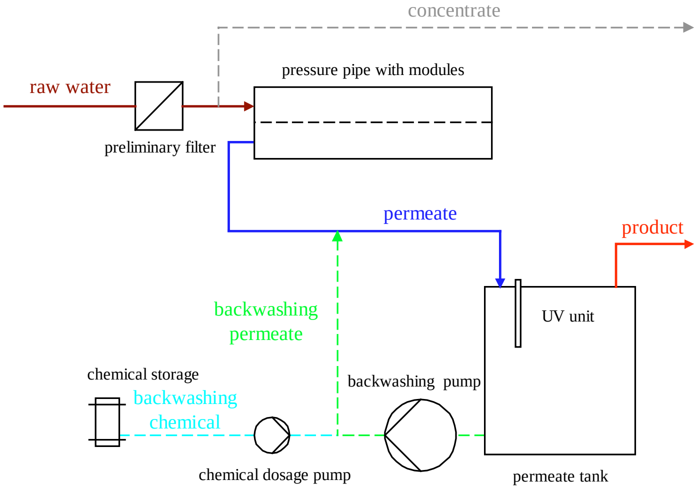

Figure 4: Schematic diagram of dead-end UF

The special interest of the dead-end tests are firstly a proof of principle for direct dead-end filtration of river water. Secondly the „ideal“ energy demand of a dead-end unit (compared to other filtration processes) shall be examined. This last feature gives the opportunity to use directly existing pressure levels (e.g. from distribution pumps within the network) for the UF.

3.3 Pilot results

In the pilot plants, the following data are logged: module inlet pressure, permeate pressure, modular pressure difference (cross-flow system), raw water temperature, raw water turbidity, concentrate turbidity (cross-flow system) and permeate turbidity. In ultrafiltration of screened or gravel filtered river water, these values are determined by the operating parameters of the system and the constantly changing raw water quality. The raw water quality is subject to seasonal and even daily fluctuations that in turn are affected by regional weather factors. Other external factors also have an influence. These all ultimately act on the parameters of permeate flow, TMP, raw water turbidity and filtration temperature. An important feature of the ultrafiltration pilot trials is the independence of permeate turbidity from all influencing factors and effect chains. The main test results from both pilot plants are shown in figures 5 and 6.

During the trial period, both pilot plants have operated largely troublefree after carrying out a wide range of optimisation work. The permeate flow rate of the cross-flow system was between 60 and 80 l/(m²h) with yields of 75 to 90 %, while the dead-end system achieved a permeate flow rate of between 40 and 70 l/(m²h) with yields of 55 to 80 %.

Seasonal variations in the temperature of the river water (4 to 30 °C) did not substantially affect the performance of the cross-flow system. However, the results of measurements on the dead-end pilot plant indicate temperature dependence of the filtration process. For water temperatures above 10 °C (April - November), dead-end filtration problems were observed only during periods of very high raw water turbidity (flood situation). These problems were exacerbated at low temperatures, so that the dead-end system could sometimes no longer be controlled by permeate flow but had to be controlled by TMP instead (November - December).

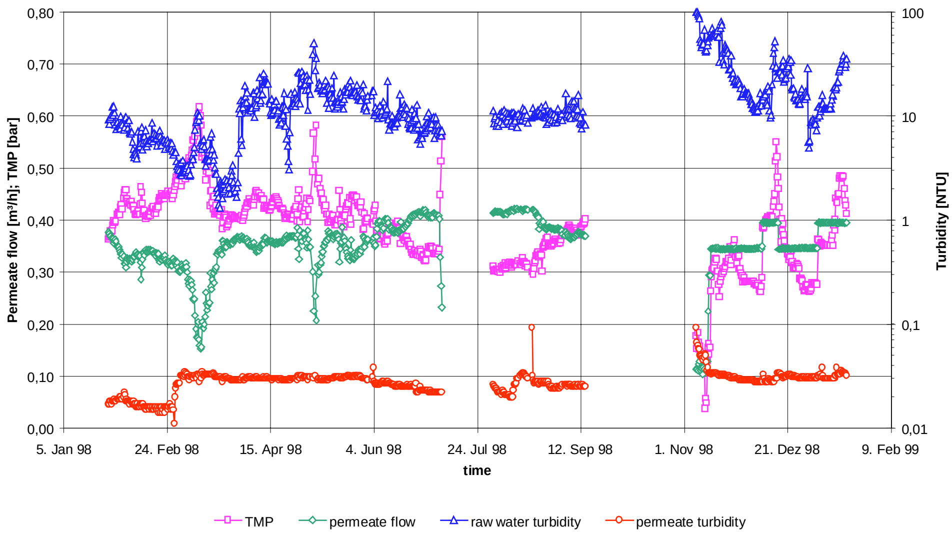

Figure 5: Main results of measurements in cross-flow UF

The cross-flow UF system was changed in design with respect to operation control mode. The system was changed from pressure-controlled to permeate flow-controlled operation from mid-September 1998 to take into account the planned scale-up of the pilot plant to industrial-scale operation. The pressure-controlled operating mode was initially chosen to assess the general filtration performance data of the membrane under the most diverse raw water conditions.

It was observed that in the dead-end plant, unlike the cross-flow plant, filtration problems tended to occur during periods of high raw water turbidity. These necessitated modifications to the backwashing system in order to make it more efficient. In fact, the backwashing systems of both pilot plants had to be adapted properly to actual service conditions to ensure stable plant operation. The modifications concerned both the operational sequence of backwashing and the selection of suitable backwashing chemicals. By judicious selection of backwashing chemicals, biofouling and fouling problems could be considerably reduced. The two pilot plants reacted to biofouling and fouling in different ways because of their different system designs and membrane materials. In the cross-flow plant, the slight use of a biocide (< 10 ppm sodium hypochlorite during backwashing) was sufficient to ensure troublefree system operation for the entire trial period without chemical cleaning. In the dead-end plant, on the other hand, biofouling and fouling problems occurred in combination, which has so far required the use and testing of different backwashing and cleaning chemicals.

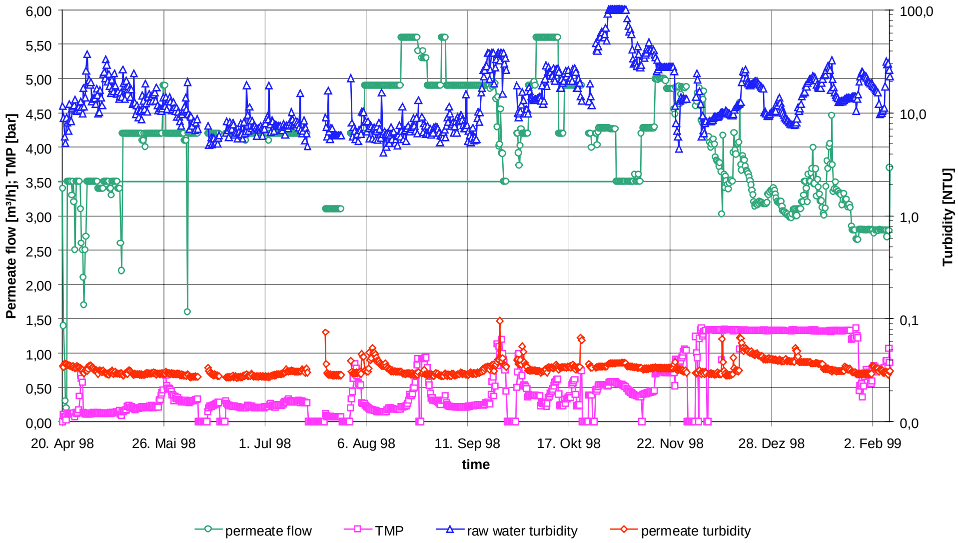

Figure 6: Main results of measurements in dead-end UF

Furthermore for the dead-end system a considerable amount of hydrodynamic optimization work was necessary in order to prevent an continuous deposition of raw water constituents on the membrane and accumulation inside the modules and the pressure housing.

Nevertheless, in every case for both systems a permeate turbidity of less than 0.1 NTU (Nephelometric Turbidity Unit) was achieved which was appreciably lower than the pure water turbidity resulting from the conventional treatment.

3.4 Main analytical findings

The permeate and pure water parameters determined in the analytical routines are shown in table 1. Apart from turbidity the analytical results for the two UF plants differed from those for the conventional treatment process only in some individual parameters (spectral absorption coefficient 254 nm, spectral absorption coefficient 436 nm).

Parameter	Prefiltered river water	Conventionally treated water	Permeate
pH	7.6	7.7	7.7
conductivity [µS/cm]	694	898	708
total solids content [mg/l]	454	597	443
content of out filtred matter [mg/l]	12.5		
SAC 254 [1/m]	7.5	3.1	7.2
SAC 436 [1/m]	0.43	0.08	0.38
total iron [mg/l]	0.23	0.09	0.01
free chlorine [mg/l]	0.12	0.17	0.04
total chlorine [mg/l]	0.09	0.41	0.06
AOX [mg/l]	0.04	0.07	0.03
COD [mg/l]	11.5	7	8.2
TOC [mg/l]	4.2	3.2	3.5
BDOC [mg/l]		0.8	0.9
microorganisms [-/100ml]	30000	36	1

Table 1: Main analytical findings

A significant difference was found in the microbiological investigation parameters. As a result of the mechanical barrier of the membrane, the permeates from the pilot plants showed significantly lower average bacterial counts than the pure water from the conventional process.

The extremely low bacterial counts and low rate of bacterial recolonization of the ultrafiltrates prior to downstream process steps (reverse osmosis) were confirmed in more detailed microbiological research by laser fluorescence spectrometry.

The bacterial recolonization of all the product waters studied, measured as biodegradable dissolved organic carbon (BDOC), was similar. However, it had been expected that ozonization in the conventional process would - through oxidation - make part of the organically dissolved carbon additionally bioavailable and so cause the BDOC to rise.

3.5 Plant engineering

In plant design the specific framework conditions and site characteristics applying to the process must also be taken into account on the basis of the piloting experience. In industrial applications (e.g. Höchst Industrial Park), the demand requirement profile, even with a large number of customers, generally exhibits considerable fluctuations. Consequently a high degree of operational reliability as well as availability have to be ensured. Figure 7 shows a block diagram with corresponding flow rates for both UF-systems.

The essential difference, particularly with regard to the equipment of the two concepts, lies in the UF unit. Because of the additional cross-flow unit, the equipment of cross-flow UF is more expensive than for dead-end UF. On the other hand, backwashing in the dead-end system requires more backwashing permeate and so the pumping station and backwashing buffer have to be larger in size. In addition, the somewhat poorer yield with dead-end UF also means that the pumping station and the preliminary filtration unit have to be designed about 10 to 20 % larger.

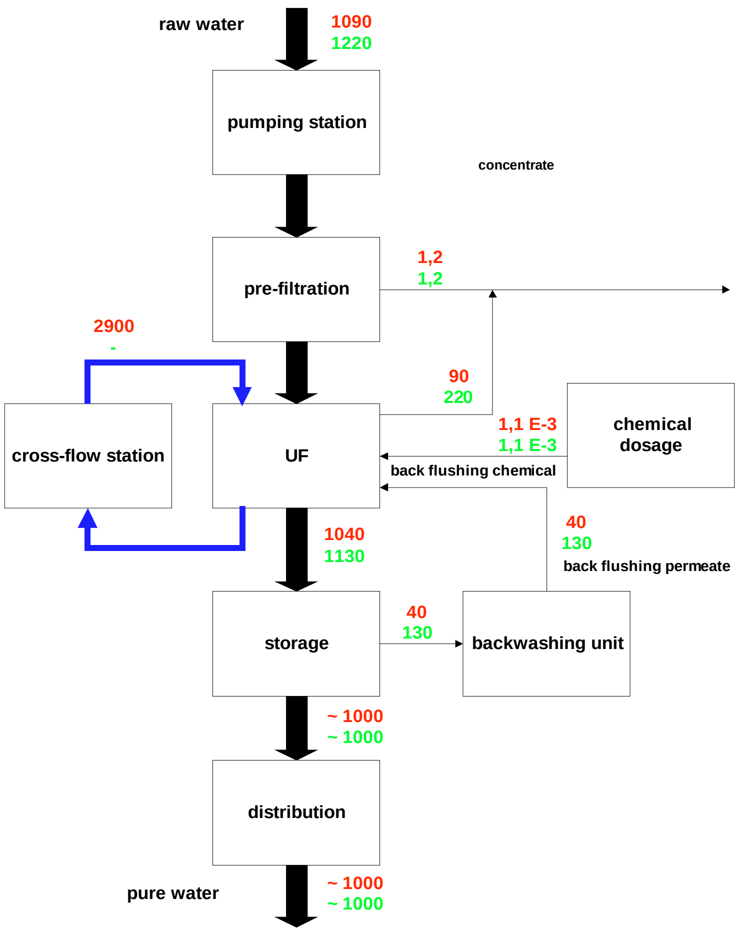

Figure 7: Block diagram and flow rates for a plant capacity of 1000 m³/h for both UF systems (flow rates in m³/h, red: cross-flow, green: dead-end)

3.6 Costs

With regard to capital outlay, the UF system concepts differ mainly in terms of module, pipework and machinery costs. The capital outlay for large-scale application of dead-end-filtration (assuming direct concentrate return to the river) is approx. 10 % below that of the cross-flow system. Compared with a conventional treatment plant the capital outlay is slightly lower with a design capacity of 1000 m³/h. Generally when comparing industrial-scale UF and conventional water treatment plants, the capital outlay greatly depends on the scale and exact nature of the process. For example ozonization is not necessarily always required in conventional water purification. With smaller units the advantage of the UF-systems in capital outlay is more significant than in large-scale projects.

The energy costs of the single-stage UF process, with 0.021 EUR/m³ for the cross-flow system and 0.019 EUR/m³ for the dead-end system (0.035 EUR/kWh), are clearly far less than those for the conventional multi-stage water treatment plant (0.08 EUR/m³). Dead-end UF is somewhat more favorable in cost terms than cross-flow UF because it does not require the cross-flow unit.

The total operating cost of the UF plants amounts to 0.25 to 0.35 EUR/m³ and is appreciably lower than that of the present treatment process (0.5 EUR/m³). The lower operating cost can be partly attributed to the smaller number of process stages, which means more straightforward processing and thus fewer operating personnel. It is also due to the fact that the UF process requires only very small amounts of process materials and additives (chemical backwashing, cleaning). A further crucial advantage for UF is the fact that there are no concentrate or waste disposal problems, since the concentrates resulting from backwashing during the UF process can usually be returned directly to the river. The sludge produced in the conventional water purification process has to be further treated to make it suitable for landfill disposal.

3.7 Process evaluation

The results show that the modular and consequently flexible UF process can generally be used for purification of virtually untreated river water. From the process engineering viewpoint, the pilot-scale results obtained with the cross-flow and dead-end plants confirm the high efficiency of both systems. The fact that the dead-end filtration plant, which has previously been used only with relatively clean surface waters or after complex pretreatment, also operates largely troublefree in the present application is a special result that should be emphasized. Nevertheless, for dead-end filtration of river water a higher flexibility of the module design with respect to process control and optimisation would be worthwile . From cost calculations based on the present trials it can be seen that UF is competitive with the conventional process. The industrial-scale plant concepts developed from the operational data are comparable. They show that the dead-end plant has an advantage in terms of capital outlay (no loop operation) while cross-flow UF has lower operating costs (reduced backwashing requirements) and – which is essential - higher process stability and consequently higher availability and reliability.

4. River Weser: Water supply for steel industry (Stahlwerke Bremen GmbH)

4.1 Project description

Stahlwerke Bremen (SwB), a major steel company, started in 1998 a cooperation with the Institute of Environmental Process Engineering of the University Bremen (IUV) for reengineering of the water supply system. After analysing the situation in producing ultrapure water from the River Weser, it was obvious that SwB needs a new water purification plant. On basis of the present state-of-the-art it has been decided to treat the river water directly with two membrane stages (ultrafiltration and reverse osmosis) as the main process steps. However, due to the lack of experiences with different surface waters these technologies have to be tested in pilot trials for specific raw water. Particularly no results for treating water from the River Weser by membrane technology were available.

On basis of the specific needs of a water purification pilot plant an extensive qualification procedure for different OEMs took place in December 1999. Axiva GmbH was engaged as a competent project partner for building a large-scale pilot plant for the treatment of water from the River Weser by the combination of direct ultrafiltration and reverse osmosis (total capacity 36 m³/h RO-permeate) and as a partner for accompanying the project. The details of the plants were fixed in the beginning of 2000 as the result of a know how transfer between all partners.

The aim of this joint cooperative venture is to acquire operating experience with the pilot plant over an extended period. In three years' time the experience gained can be used in a full-scale plant replacing existing conventional plant technology to produce ultrapure water with the new, modern treatment method. Consequently, the overall performance of the process (economy, water quality, suitability with respect to process stability, availability and higher convenience) has to be considered carefully within the framework of the steel processing industry. The pilot plant is being built up now and is beeing started up in July 2000.

4.2 Plant Configuration

The new process for process water production from river water is divided into three stages: prefiltration, ultrafiltration and reverse osmosis (see figure 8).

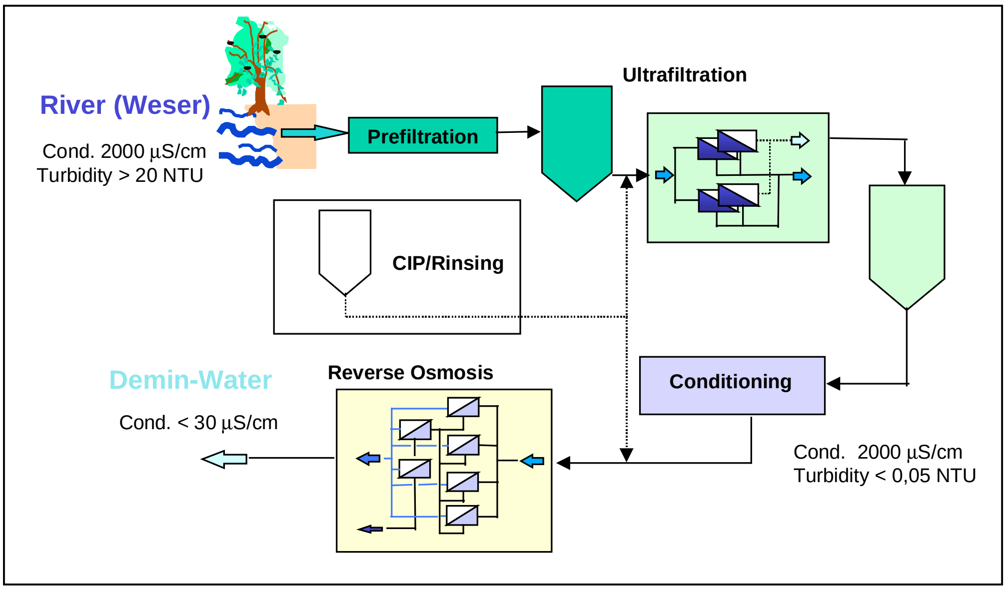

Figure 8: Process water production from river water by UF and RO

Taking a view to the plant, the main focus is on the ultrafiltration, because of its innovative character for this application. Thus, the pilot plant have the following features: The ultrafiltration is separated into two independent lines using two different hollow fibre membrane elements (polysulfone and cellulosetriacetat). Furthermore, the plant provides several optimisation opportunities with respect to the pilot character of the operation period, particularly for cleaning (feed-flash, permeate backwashing, chemical backwashing). The UF-unit can be operated either in cross-flow mode or dead-end mode alternatively.

4.3 Plant Description

In the first stage the raw water is passed through an approximately 100 µm coarse filter. A backwashable filter is used here, which can be cleaned without interrupting the operation of the plant. Furthermore a heat exchanger controls the feed temperature.

The prepurified raw water is passed to the next filtration unit, which comprises unltrafiltration units arranged in parallel. These consist of a closed loop and operate on the feed & bleed principle. The heart of the UF units are 12 four end membrane modules (hollow fibre membranes from Koch and Daicen/Celgard) arranged in parallel, which operate vertically at a very low flow rate (about 0.2 m/s) on the cross-flow principle.

Figure 9: UF-hollow-fibre module

Figure 10: 3D-Model of UF-unit

This process variant operates with considerably reduced specific energy consumption - comparable to that of a dead-end system (0.3 kWh/m³) – but also permits direct, reliable use of ultrafiltration for pretreating river water before a desalting stage.

The resultant permeate flows as pure water initially into an intermediate tank, from which the permeate is taken for periodically necessary backwashing. The retained raw water constituents remain in the concentrate and form a layer on the membrane that is removed at regular intervals by backwashing with permeate.

In this operation a suitable biocidal/cleaning backwashing chemical (e.g. sodium hypochlorite, NaOCl) is metered in-line. This prevents contamination of the permeate produced and of the remaining concentrated raw water with substances that form adsorbable organic halogen compounds. The concentrate is taken as a continuous bleed flow from the loop of the UF and can normally be returned to the river. The water used in backwashing (about 4 % of the permeate volume) accumulates as waste water but can be treated further or concentrated.

Before the UF permeate is fed to the reverse osmosis (RO) unit, it is necessary to condition the water (e.g. pH adjustment, scaling control) so as to ensure reliable optimum performance of the RO unit.

Figure 11: Spiral wound-modules

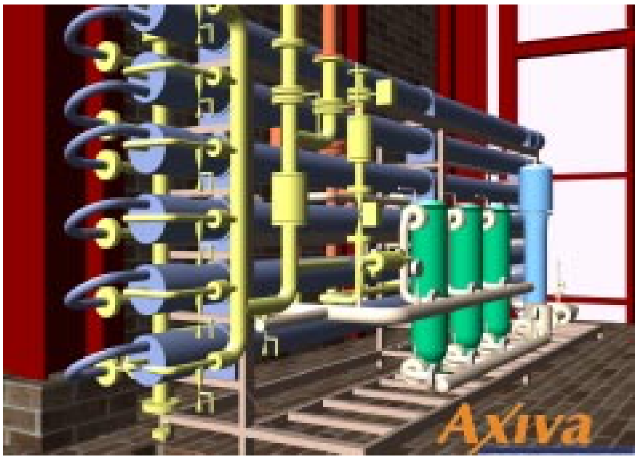

Figure 12: 3D-Model of RO-unit

The stream of water is then passed through a security filter (5 µm) to the reverse osmosis unit in order to save the RO-membranes in case of broken hollow fibres in the ultrafiltration plant. The necessary operating pressure is provided by the speed-controlled high-pressure pumps. The RO plant consists of several units of graded concentrations with spiral wound modules of the standardized type 8040 arranged in series and in parallel. This type of module is state-of-the-art for reverse osmosis plants for water supply because it has a high volume-specific packing density and offers the possibility of using membrane modules from different manufacturers directly because of its standardized design. The RO unit is controlled primarily by the concentrate, a yield (ratio of permeate flow to feed flow) of up to 90 % being achieved.

Both membrane plants are cleaned and washed automatically using a central cleaning and washing unit and the individual feed and circulation pumps of the UF and RO units.

5. Summary

The economic combination of ultrafiltration and reverse osmosis for the production of deionized water from surface waters saves energy compared to more expensive conventional process combinations and largely avoids the formation of waste. Another advantage is that owing to the modular construction of membrane technologies there is no need to shut down plants completely for maintenance or cleaning purposes. The use of spring or ground water as an alternative source for direct feeding of the RO unit is not necessary.

With the new concept companies are given the opportunity to install a new, low-cost, tailor-made system solution to the production of process water.