

Desalting a process cooling water using nanofiltration

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Abstract

The cooling water system of a chemical plant of Akzo Nobel is a partly open system. The site is located at the North Sea. The air in contact with the cooling water contains seawater droplets dissolving and increasing the chloride concentration. The cooling water contains chromate to protect the installation for corrosion. Nevertheless, the chloride concentration in the cooling water may not exceed 50 ppm. To maintain a constant chloride concentration level, a part of the cooling water should be drained and replaced by de-mineralized water. However, the drainage of chromate is limited by governmental regulations. This paper describes a systematic approach from problem definition to the membrane process design encompassing membrane module pre-selection, lab-scale proof of principle and on-site pilot demonstration, the latter to characterize the fouling and scaling potential of the feed solution. Finally, the paper discusses various membrane process design options. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Cooling water; Akzo Nobel; Nanofiltration

1. Introduction

At a plant of Akzo Nobel located at the North Sea, the cooling water contains chromate to prevent the installation for corrosion. The cooling water system is a partly open system. The water is cooled evaporatively by a gas/liquid contactor by air that contains small droplets of seawater. These droplets dissolve in the cooling water and increase the chloride concentration. The maximum allowable chloride concentration at which the system is designed is 50 ppm. At the start of the project, the chloride concentration already passed this maximum.

The simplest technical solution is to drain a part of the cooling water to the sewage and replace it by de-mineralized water. The government allows the site to drain a maximum of chromate per day. The intake of chloride via seawater droplets requires a purge resulting in a chromate release which is about 20 times the maximum allowable amount.

A second solution is to transport the drain to a chemical wastewater treatment company. However, the anticipated costs or high and an on-site treatment technology has economical benefits.

The preferred method is to separate chromate and chloride selectively from the cooling water by a unit operation. In the past, an ion exchange unit was installed which was able to remove the chromate from the cooling water. After a few years of operating, the unit was shut down because the

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selectivity of the ion exchange material for chromate was not high enough to obtain the stringent requirements. Also operational problems due to organic fouling of the ion-exchange beds were observed.

A different potential solution — to be described in the following — is to keep the chromate in the cooling water, but purging the chloride selectively. Nanofiltration could solve this problem because it allowed to separate mono from multivalent ions [1,2]. To demonstrate the reliability of the technique and to collect data for a full scale unit at the site, lab scale and pilot plant experiments were performed. Fig. 1 describes a schematic flow diagram of the cooling water. The G/L contactor introduces excess chloride via the seawater droplets. Part of the circulation flow is fed to the nanofiltration unit purging NaCl selectively while retaining chromate. The retentate from the membrane process returns to the cooling water system. The permeate is purged to the sewage water system in accordance with governmental regulations.

This paper describes a systematic approach to determine the feasibility of applying nanofiltration to the described separation problem. The approach chosen is characteristic for the successful design and implementation of a membrane process. The systematic is visualized in Fig. 2 and combines the use of,

- a proprietary performance database of Akzo Nobel containing performance data on NF and RO modules;
- models predicting [3] the module performance of nanofiltration membranes based on membrane characteristics, such as, surface charge

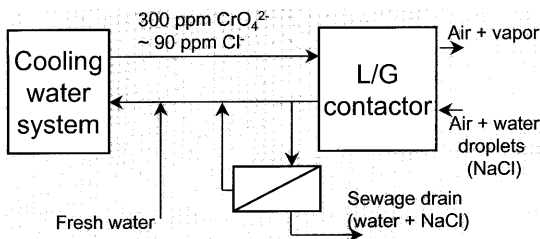


Fig. 1. Process flow diagram showing the nanofiltration unit to purge water and NaCl while retaining chromate inside the cooling water system.

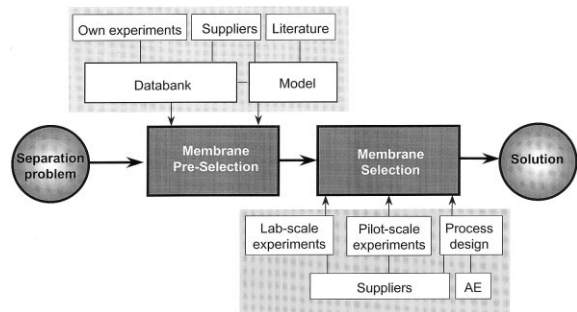


Fig. 2. Schematic visualizing the systematic approach from problem definition to problem solution.

density, membrane top-layer thickness and pore diameter;

- lab-scale experiments characterizing the performance of pre-selected membranes with synthetic feed solutions;
- on-site pilot plant test to determine on real solutions, whether one can expect scaling or fouling problems; and
- process design studies to obtain the most economic module arrangement while maintaining operational flexibility to compensate for unpredictable performance losses due to fouling or scaling.

2. Experimental

2.1. Laboratory experiments

The laboratory experiments have been performed with a pilot-scale installation. The installation is equipped with a frequency converter allowing to control the crossflow velocity. The pressure can be varied with a pressure release valve. The desired temperature is maintained by a cooling water system that is controlled by a PLC. The system runs in a total recycle mode, returning retentate and permeate to the feed vessel. The produced retentate and permeate streams will be circulated back to the feed vessel so that the flux and retention will be determined at a constant feed concentration.

The spiral wound membrane modules used for the experiments are, (a) Desal 5 DL, type 2540F purchased from Desalination Systems Inc; (b)

Table 1

Average anion composition and pH of the cooling water tested during the lab-scale proof-of-principle phase of the project

Component	Concentration (ppm)
CrO_4^{2-}	300
SO_4^{2-}	1000
Cl^-	80
NO_3^-	300
pH	8.5

DOW/Filmtec NF45, type 2540 purchased from DOW/Filmtec Germany.

Both types can be used up to 45°C, a pressure of about 40 bar and in a pH range of 2–11. The membrane area of the modules is 2.5 m².

Three experiments were performed, namely, a long term and circulation experiment with the Desal module, a circulation experiment with the Dow module and a desalination experiment with the most suitable module. The applied crossflow for both modules was 1000 l h⁻¹. The temperature was maintained at 20°C. The experiments were performed with actual cooling water from the Akzo Nobel plant. Table 1 lists the feed water composition.

Samples of the feed, permeate and retentate were taken after 0.5 h of stabilizing of the mem-

brane module performance and flushing the dead volume of the spiral wound module. The samples were analyzed on chloride, sulfate (ion chromatography) and on chromate (Flame-AAS).

2.2. On-site pilot plant trial

The experiments on-site were performed with a rented pilot-scale installation of AMA Filter/NL. This installation can operate larger membrane modules with more membrane area compared with the lab-scale pilot. The pressure can be varied with a pressure release valve. The crossflow (3 m³ h⁻¹) cannot be varied, however. During the desalination, the system runs in a single pass mode returning the retentate to the cooling water system and discharging the permeate to the sewage. When the clean water flux (CWF) and cooling water versus pressure curve are determined, the system runs in a total recycle mode returning retentate and permeate to the feed vessel. Fig. 3 shows a schematic drawing of the pilot plant.

To determine the long-term influence of the cooling water on the membrane, the permeate flux is monitored as a function of time by maintaining the pressure at a fixed level. The permeate flux data are corrected for the temperature influence considering only the viscosity changes of the wa-

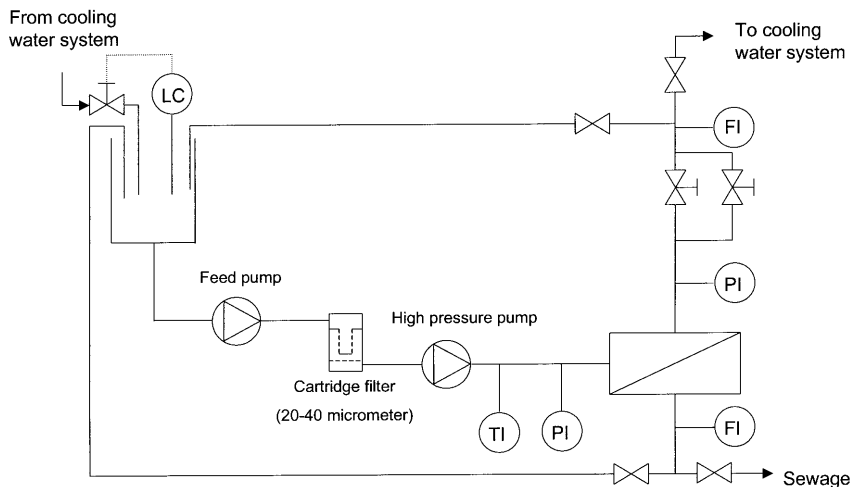


Fig. 3. Process flow diagram of the pilot plant (rented from AMA Filter/NL) operating during on-site over a period of about 3 months.

ter but neglecting the influence of the dissolved salts. Determining, the clean water flux and the magnesium sulphate retention monitors the membrane characteristics. The separation performance of the membrane with cooling water is studied by determining the permeate flux versus pressure curve and by determining the chromate and chloride retention. Later, we will present these data cross-plotted in a graph showing the retention of a particular ion versus the flux belonging to that feed pressure.

The spiral wound membrane module applied in the pilot plant testing is DOW/Filmtec NF45, type 4040. This type is comparable with the type used during laboratory testing but houses a larger membrane area of 6.5 m².

3. Results and discussions

3.1. Lab experiments

The following experiments were carried out in sequence on a pilot plant available at our process laboratories using water samples shipped from the site,

1. total recycle experiment with a Desal 5 DL module at 90 ppm chloride;
2. total recycle experiment with a Dow/FilmTech NF45 module at 90 ppm chloride;
3. desalination experiment with NF45 module to reduce the chloride content from 90 to 50 ppm; and
4. detailed characterization of the flux–retention relationship for chloride and chromate at 50 ppm.

3.1.1. Total recycle experiments with a Desal 5 DL module

Total recycle experiments (permeate and retentate recycled back to feed tank) were carried out to determine the long-term performance of the spiral-wound modules. The feed pressure was fixed at 20 bar resulting in a permeate flux of approximately 200 l h⁻¹ (recovery, 20%). The permeate flux was almost constant during the whole experiment. A slight flux increase from 84 to 87 l m⁻² h⁻¹ was observed.

The retentions for chromate and chloride were constant during the experiment as well. The observed retention for chromate was 99.0% and for chloride 78%. The retention for chloride was particularly high. Experimental experience shows that in the presence of these concentrations of multivalent ions, the retention for chloride is normally lower. Besides chloride, another monovalent anion is present in the solution, i.e. nitrate. It has nearly the same size including hydration shell and the same charge. We found that the retention for nitrate was significantly lower than chloride, negative even ranging from about –70% at low fluxes to –20% for higher fluxes. Such multi-component effects cannot be predicted by the current models and we therefore have no explanation for this experimentally observed phenomenon.

After the long-term characterization with the real feed stream, the module was characterized again with de-mineralized water and a standard solution containing MgSO₄. The permeability increased from 4.2 to 4.8 l m⁻² h⁻¹ bar⁻¹ and the MgSO₄ retention increased from 99.0 to 99.4%. The reason for this performance alteration is unclear, however, the characteristics moved towards the standard membrane module specifications.

3.1.2. Total recycle experiments with a Dow/Filmtec NF45 module

The Dow module has a lower permeability compared with the Desal module. To compare the modules, the feed pressure was adjusted to operate at equal recovery of approximately 20%. At 30 bar, the flux was 90 l m⁻² h⁻¹ (recovery, 22.5%). The slope of the permeate flux versus pressure curve was 2.9 l m⁻² h⁻¹ bar⁻¹ which is 40% lower than the slope of the Desal module (4.7 l m⁻² h⁻¹ bar⁻¹).

The influence of the permeate flux on the retention of the components was studied by taking samples at a recovery of 22.5% ($P = 30$ bar, flux = 90 l m⁻² h⁻¹) and at a recovery of 8% ($P = 10$ bar, flux = 32 l m⁻² h⁻¹). The influence of the flux on the retention was significant. The chromate retention decreased from 98 to 96.5%. However, the chloride retention decreased enormously, from 50 to 13%. To maximize the chloride purge, this decrease in retention is desired.

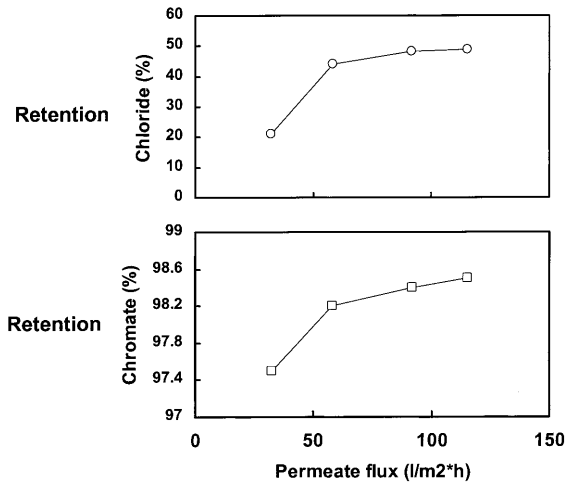


Fig. 4. Membrane performance characteristics plotted as retention vs. permeate flux for chloride and chromate at 50 ppm chloride feed concentration.

However, the decrease in chromate retention must be carefully taken into account.

The experiment with the cooling water did not show any influence on the membrane performance. The clean water flux and the MgSO_4 retention before and after the experiment were approximately the same. However, from such experiments with a limited amount of feed solution one must not conclude that fouling will not occur during continuous on-site operation.

3.1.3. Desalination experiments

Eventually, the cooling water at the Akzo Nobel plant has to meet a lower chloride concentration (between 45 and 50 ppm). Therefore, an experiment was necessary to determine the influence of a lower chloride concentration on the separation.

The desalination was carried out with a constant feed level in the vessel in a batch mode. This means that the produced permeate is discharged and fresh water has to be added to the feed vessel to remain a constant level in the vessel. The required amount of fresh water can be calculated according to Eq. (1):

$$\frac{V_w}{V_b} = \frac{-\ln(C_0/C_t)}{(1-R)} \quad (1)$$

where V_w/V_b is the wash ratio, C_0 the starting concentration chloride, C_t the required end concentration chloride, and R is the the retention of the membrane module for chloride. One has to keep in mind that the retention most likely is a complex function of the permeate flux and the feed concentration.

The desalination was carried out at 30 bar (20% recovery) and therefore, the chloride retention was assumed to be 50%. The required chloride concentration was 50 ppm resulting in a wash ratio of 1.2. After the desalination, again a total recycle experiment was carried out. The chloride concentration had no influence on the permeate flux versus pressure curve. The slope of the curve was equal to the experiment at 90 ppm chloride, namely $2.9 \text{ l m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$.

To determine the influence of the permeate flux on the retention of the various components, samples were taken of the permeate and retentate at a pressure of 10, 20, 30 and 40 bar. The observed retention for chromate slightly increases compared with the experiment with 90 ppm chloride (97.5% compared with 96.5% at 10 bar and 98.4% compared with 98.0% at 30 bar). The retention for chloride at low pressure ($P = 10$ bar) slightly increases from 13 to 20%, but at higher feed pressure the obtained retentions are equal.

Fig. 4 shows the retention for chloride and chromate plotted as a function of the permeate flux. The retention of the components increases with increasing permeate flux. The increase in retention with flux is caused by a decreasing influence of the diffusive flux on the total solute flux through the membrane compared with the convective contribution. It is important to notice that a slight decrease in chromate retention may not appear to be significant in absolute numbers, but for the final system design, it may represent the fact that the system has a performance within or outside the maximum allowable chromium purge. We have therefore identified a critical flux of about $60 \text{ l m}^{-2} \text{ h}^{-1}$ above which the chromate retention remains close to constant. Later system design calculations are based on this minimum flux value.

3.2. Pilot plant trial

The lab scale experiments demonstrated the feasibility of applying nanofiltration as a possible technique to remove chloride from the drain and rejecting chromate. However, a long-term experiment is required to get more information about the lifetime of the membranes and to determine the proper process and eventual cleaning conditions. Also the cooling water was not at specification (chloride concentration > 90 ppm). A long-term desalination experiment with a pilot plant will solve both issues, the pilot experiments will be operated

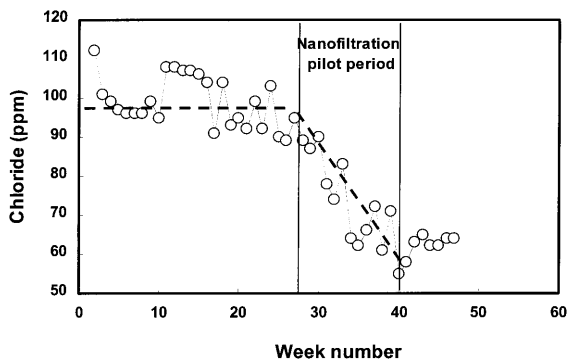


Fig. 5. Chloride concentration in the cooling water system as a function of time. The nanofiltration pilot experiment was performed from week 28–40 to demonstrate the separation of chloride and chromate and to reduce the absolute chloride level.

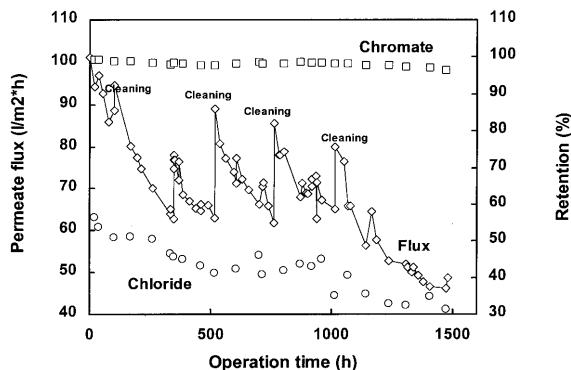


Fig. 6. Performance data of the pilot plant run (week 28–40) presenting the permeate flux and the chloride and chromate retentions as a function of time. Peaks in the flux indicate membrane cleaning.

such that the ultimately required NaCl level will be reached.

The pilot plant experiment — having a system directly operating on a bleed stream of the cooling water system — was performed over a period of about 90 days. In this period, the installation was in operation for 1460 h, which means that 70% of the available time effectively was used to desalt the cooling water. During the period, the installation was not in operation for 28 days caused by several technical problems such as a too low feed flow towards the nanofiltration unit, pump failures caused by a defect outlet valve and a broken driving shaft of the pump. The pilot plant system was operated at constant pressure (instead of constant permeate flow) for the simple reason that the urgency of the testing allowed only the renting of constant pressure system.

3.2.1. Desalination

Fig. 5 shows the development of the chloride concentration over a period of about 1 year. During the weeks 28–40, the pilot plant operated and desalted the cooling water from about 100 ppm down to 50 ppm chloride. Fluctuations in the chloride concentration level before and after the pilot trial result mainly from the addition or closure of sections of the cooling water circuit. Fluctuations in the chloride concentration levels during the pilot plant will be explained in more detail in the following.

3.2.2. Permeate flux data

The pilot period was started by determining the clean water flux, magnesium sulfate retention and the permeate flux versus average pressure curve of cooling water. Both the CWF and $MgSO_4$ retention were within the specification of the supplier. The permeability of the cooling water was almost equal to the permeability of clean water. These results were comparable with the preliminary results of the lab scale experiments as well. According to the characterization, the membrane module was within specification and suited for this application. Therefore, the pilot scale experiments were started and the produced permeate was discharged to the sewage. Fig. 6 shows the permeate flux as a function of the operation time during the pilot period.

Table 2

Clean water fluxes of membrane module as a function of operation time after chemical cleaning

	Operation time (h)	Clean water flux ($\text{l m}^{-2} \text{ h}^{-1} \text{ bar}^{-1}$)
Start	0	3.5
After cleaning 1	187	3.6
After cleaning 2	517	3.6
After cleaning 3	763	3.5
After cleaning 4	1013	3.3
After cleaning 5 ^a	1480	3.2

^a The acid cleaning was not performed.

The pilot system contained a cartridge filter before the membrane module to protect the module from fouling of larger particulate. Depending on the sieve size capacity of the cartridge, we applied 20, 30 and 40 μm filter cartridges. This caused the resistance of the filter to increase in time resulting cavitation of the high-pressure pump. Therefore, the cartridge was replaced between 100 and 200 h operation. The replacement time depended on the sieve size capacity of the cartridge and decreased with increasing sieve size capacity.

During the pilot period, at the time when the filter cartridges were exchanged, the module was flushed several times with de-mineralized water and four cleaning actions were performed. Flushing with de-mineralized water showed only little influence on the permeate flux increasing with approximately 5–10 $\text{l m}^{-2} \text{ h}^{-1}$ only. However, within 20-h operation, the flux increase disappeared again. The cleaning actions were more effective. In general, it can be concluded that the effect of a cleaning lasted approximately 200 h. For example, before the cleaning the permeate flux was 65 $\text{l m}^{-2} \text{ h}^{-1}$, after the cleaning 85 $\text{l m}^{-2} \text{ h}^{-1}$ and after 200-h operation, the flux was again 65 $\text{l m}^{-2} \text{ h}^{-1}$.

The cleaning agents applied were Ultrasil 10 (a caustic agent containing chelates and wetting agents) and Ultrasil 70 (an acid agent containing wetting agents and emulsifiers) from Henkel Eco-lab. Determining the CWF before and after the cleaning screened the effectiveness of the procedure and is summarized in Table 2. The experiments showed that the acid agents had no influence on

the performance of the membrane and the membrane fouling could be removed with the caustic agent: after each cleaning, the permeability had approximately the same value as the initial value. However, the permeability of cooling water tended to decrease as a function of time which resulted in a lower permeate flux at the applied pressure. It seems that at the membrane surface, a pollution is present which does not affect the CWF, but influences the permeability of cooling water and cannot be removed by the applied cleaning agents. Since this phenomenon is not well understood, further optimization of the cleaning procedure with, for example, enzymatic cleaning agents, must be performed.

3.2.3. Retention data

During the desalination, three effects were observed. The concentration of chloride decreased as intended, the retention of chloride decreased and the permeate flux decreased. The decrease of the retention is related to the decrease of the permeate flux. When the permeate flux decreases, the influence of the diffusive flux on the total solute flux through the membrane increases compared with the convective contribution. At the concentration levels considered, the relationship between the permeate flux and the chloride retention depends only little on the chloride concentration. The retention decrease from 45 to 30% normally has a positive effect on the performance of the desalination. However, also the permeate flux decreased which meant that the daily chloride discharge was equal when a higher permeate flux in combination with a higher chloride retention was observed.

During the pilot study, the chromate concentration in the cooling water system remains constant, whereas the retention decreases from 99 to 96.5%. The explanation for this phenomenon is the same as for the decrease of the chloride retention — permeate flux decrease causes the increase of the diffusive flux with respect to the convective contribution the decrease in chromate retention with decreasing flux is a significant performance relationship to be considered during the system design procedure — a small decrease in chromate retention may cause the system under consideration to be within or outside the specifications.

4. Design calculations and discussion

A number of design calculations have been performed in order to design a flexible nanofiltration installation which is able to meet the following specifications,

the installation should be able to remove 3500 mg h^{-1} chloride, but should also be capable to remove higher amounts of chloride in case of (temporary) higher chloride intake;

the amount of chromium drained to the sewage water system should be less than 10 g per day and probably even considerably less, because part of the allowed chromium drainage is already supplied by groundwater; and preferably, the chloride and chromate containing water in the buffer tank (about 1200 m^3) should be reused in the cooling system.

In contrast to the pilot experiments on location, we designed the system to operate at a constant flux of $60 \text{ l m}^{-2} \text{ h}^{-1}$ since the retention of chromate drops at lower flux values.

The following performance parameters were determined in the design calculations.

Maximum chloride intake: the maximum chloride intake is equal to the amount of chloride present in the permeate which will be drained to the sewer. In a two-stage process, this is the permeate of the second stage of the nanofiltration. The amount of chloride is calculated by the permeate flow multiplied by the chloride concentration in the permeate.

Chromium drain: The chromium drain is equal to the amount of chromium present in the permeate which will be drained to the sewer. In a two-stage process, this is the permeate of the second stage of the nanofiltration. The amount of chromium is calculated by the permeate flow multiplied by the chromium concentration in the permeate.

Permeate surplus: the permeate surplus is only an issue in a two-stage process. In the first stage of the nanofiltration, permeate is generated which will serve as feed for the second stage. The required amount of feed in the second stage depends on the recovery of this stage (for a fixed flux and membrane area). The higher the recovery in the second stage, the lower the

amount of feed required. To be able to operate with a range of recoveries, sufficient membrane area should be installed in the first stage in order to provide the required feed for low recoveries. The permeate surplus at higher recoveries will be directly returned to the cooling system without a treatment in the second stage.

Feed from buffer tank: to keep the cooling water system on specification, Methanor has drained cooling water in a buffer tank. This tank contains now 1200 m^3 water with 180 mg kg^{-1} chromate and 58 mg kg^{-1} chloride. The concentration level of chromate is such that treatment is necessary before disposal is possible. If the maximum chloride removal capacity is higher than the actual chloride intake, chloride-containing water can be fed from the buffer tank into the cooling system. The possible amount of feed from the buffer tank can be calculated by subtracting the actual chloride intake from the maximum chloride intake and divide it by the concentration of chloride present in the buffer tank. The amount of feed from the buffer tank replaces part of the fresh de-mineralized water intake.

Chromate added from buffer tank: by adding solution from the buffer tank besides chloride chromate also is added to the cooling system. This leads to an increase in chromate concentration. Under normal circumstances, fresh chromate needs to be added regularly to the cooling system to keep the chromate concentration at a level of $250\text{--}300 \text{ mg kg}^{-1}$. The amount of chromate added from the buffer tank has been calculated in order to be able to compare it with the amount of fresh chromate which is normally taken in.

The process design calculations were performed for a single-stage and two-stage nanofiltration system as shown in Fig. 7. The calculations are based on mass balances around the membrane modules considering the retention data obtained during the experimental program.

A single-stage nanofiltration process with a 2.2 m^2 Dow/Filmtec NF45 module can just meet the chloride specification and keep the chromium drain below 10 g per day. However, this design is very critical and the specifications cannot be met,

if the chromate retention is even a little lower on full scale. This also holds, in case, the chloride intake is (temporarily) somewhat higher than expected and the government imposes a further restriction on chromate drainage. The Desal 5 DL membrane is in no case able to meet the requirements in a single-stage process. Recirculating a part of the retentate (to maximize the flow through the module and to minimize concentration polarization) results in an increase in the average feed concentration ultimately causing the amount of chromium drained to increase. Therefore, we proposed a two-stage nanofiltration process.

The Dow/Filmtec NF45 has a better performance than the Desal DL5 membranes in chloride removal and chromium drainage due to its lower retention characteristics for chloride. Therefore, the Dow membrane has been applied for the design of the two-stage nanofiltration installation.

A two-stage nanofiltration process with one 6.5 m² module in the second stage is able to remove a chloride intake of 6000–10 000 mg h⁻¹ with a chromium drainage of only 2 g per day. The chloride removal capacity of the installation is

considerably larger than the estimated chloride intake of 3500 mg h⁻¹, whereas the chromium drainage is considerably lower than required. This design strategy anticipates deviations in chloride intake and further chromium restrictions by the government. Moreover, it allows reuse of the chromate and chloride containing water from the buffer tank in the cooling system if the average chloride intake matches the estimated chloride intake. In that way 0.6–1.2 MNLG disposal costs can be saved due to reuse, besides the yearly disposal costs of 0.25–0.5 MNLG in the future.

The 3–1 module configuration (3 modules in first stage, 1 module in second stage) allows a more flexible operation compared with a 2–1 module configuration because a broader range of recoveries can be applied in the second stage. The recovery in the second stage determines the amount of chloride, which can be removed by the process. According to lab tests in Arnhem, the chromium drain is nearly independent of the recovery up to a recovery of 0.7–0.8. During the reuse of the water from the buffer tank, high recoveries could be applied to maximize the chloride removal capacity. After, all water from the

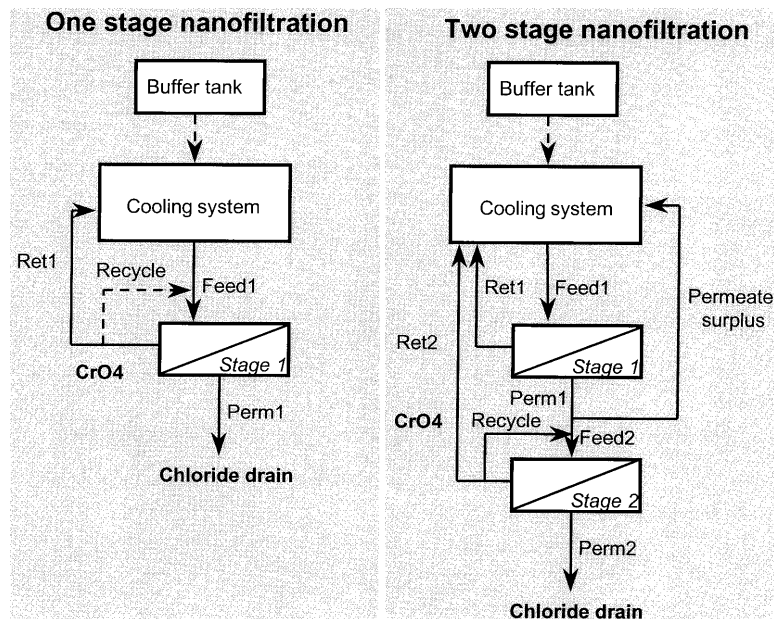


Fig. 7. Schematic representing single-stage and two-stage membrane process.

buffer tank had been reused, the recovery could be decreased to 0.4 corresponding with 6000 mg h^{-1} chloride removal capacity.

With the chloride removal capacity of the 3–1 module configuration, it will take about 2 years before the 1200 m^3 in the buffer tank has been totally reused in the cooling system. By installing a 4–2 module configuration, the time for reuse can be reduced to 7–9 months. However, the installation will have a large overcapacity ($15\,000$ instead of 3500 mg h^{-1}) once the buffer has been reused.

It is important to remain above a minimum flux level ($60 \text{ l m}^{-2} \text{ h}^{-1}$) in the first stage because the chromate retention decreases strongly at lower fluxes. During the pilot runs, the flux appeared to decrease due to membrane fouling. To remain above $60 \text{ l m}^{-2} \text{ h}^{-1}$ periodic cleaning of the membrane is necessary. The first attempt to clean the membrane was reasonably successful. Therefore, the nanofiltration installation should contain automatic cleaning facilities. The cleaning frequency, amount of cleaning and type of cleaning agent should be adjustable and should be optimized during long-term operation of the actual installation.

The nanofiltration installation with a 3–1 module configuration has been chosen as a basis for the quotations, for which two membrane contractors have been asked.

5. Conclusions

The lab-scale proof-of-principle experiments and

the pilot plant study have proven the feasibility to separate chloride selectively from chromate by applying nanofiltration. The study demonstrated that it was possible to desalt the cooling water and that the daily intake of chloride could successfully removed. At the end of the pilot run, the chloride concentration in the cooling water was at 50 ppm, which is at specification.

Based on the results, design calculations were performed to determine the amount of drain to remove the daily intake of chloride. These calculations showed that a single-stage system using a Dow/FilmTech membrane module was just able to meet the required specifications. However, due to system sensitivity to feed composition fluctuations, this design was not further evaluated. A two-stage nanofiltration unit could remove easily the daily chloride intake with a chromate drain of less than 20% of the maximum allowable amount per day.

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