Abstract
The Wasserwerk des Kreises Aachen in Roetgen, Germany operates with financial help of the German Ministry for Education and Research and with scientific support of the IWW (Muelheim, Germany) a large scale membrane pilot plant. This pilot is equipped with twelve 6 m long pressure vessels resulting in a membrane area of about 1,620 m² to produce about 150 m³/h of filtrate. The pilot plant was operated first with flocculated reservoir water as feed. The results show that this is a reasonable process especially if the backflush water of the plant is further treated with another membrane plant to achieve high overall recoveries up to 98–99%.

Monitoring of membrane integrity is an important topic in this research. Every pressure vessel of the pilot can be connected to a particle counter by switching magnetic valves automatically. Corrupted fibres were detected by particle counting after about 8 month of operation. A correlation between the number of broken fibres and particle concentration in the filtrate could not be established and may not exist as it is discussed in this paper.

Keywords
Flocculation; membrane integrity; particle counting; ultrafiltration

Introduction
The drinking water treatment plant in Roetgen, Germany of the Wasserwerk des Kreises Aachen (WdKA) will be modernized to enhance the particle removal efficiency. In this plant reservoir water is treated by flocculation and two-stage deep bed filtration (Figure 1). To enhance the efficiency membrane filtration (micro- or ultrafiltration) is taken into consideration. The capacity of the extended plant would be 6,000 m³/h. Thus, the micro- or ultrafiltration plant would be one of the largest in the world.

In a former project 3 pilot plants (5–10 m³/h) were operated for about 3 years (1996–99) treating water after the 2nd filtration step, after the 1st filtration step and flocculated raw water (Panglisch et al., 1998a,b; Gimbel et al., 1999). By treating water after the first filtration step KMnO₄ was added to oxidize the dissolved manganese. The cake layer on the membrane surface formed by the MnO₂ particles allowed a very stable operation of the UF-systems. Using just flocculated raw water as feed a stable operation at lower fluxes were achieved as well. Thus it was decided to build a large scale technical plant with a capacity of about 150 m³/h which will be operated with water after the first filtration step and with flocculated reservoir water. Results of the operation with flocculated reservoir water will be shown in this paper.

Pilot plants
The large scale pilot plant is equipped with twelve 6 m long pressure vessels arranged in two rows (Train 1 and Train 2). Every pressure vessel contains 4 UF-elements \( (d_{\text{fibre}} = 0.7–0.8 \text{ mm}) \) resulting in a membrane area for a pressure vessel of 135 m² and a total membrane area for the pilot plant of about 1,620 m².
As shown in Figure 2 flow meters are installed at the two feed entries and also at one of the two filtrate outlets. This allows to monitor the performance of every single pressure vessel.

To monitor the filtrate quality two particle counters are installed. Particle counting was performed in the range of 0.05–0.2 µm using the HSLIS M50 sensor (Particle Measuring Systems) and in the range of 0.7–500 µm using a counter from Analytische Meßtechnik (Klotz). Sampling points for particle counting were installed at the two outlets of every pressure vessel (PV) (Figure 2). The two tubes for one pressure vessel were connected in the middle of the vessel and the tube then leads to a magnetic valve just in front of the particle counters. The program for operation of the pilot allowed to switch the 12 magnetic valves in a way that the whole plant, one side of the plant (6 PV) or just one pressure vessel could be monitored. The continuous flow of the tubes from the pressure vessels not monitored were drained. The magnetic valves were shut for the time of a backflush and for about 5 minutes after the backflush.

Reservoir water to which aluminium sulfate is added as a flocculant is fed to the pilot since start-up in November 1999 until October 2000, when the pilot was switched to treat water after the first filtration step.
Results

Pilot plant operation

Performance of membrane pilot plant. The performance data shown in the figures below cover the time from March 14 through July 2, 2000. In the beginning of this period the pH after flocculation was 5.3, which is the natural pH of the raw water after adding about 4 mg Al/L. Figure 4 shows that at this low pH the Al concentration of the filtrate is about 1 mg/L. The DOC removal is about 50% and is in the order of the removal in the drinking water treatment plant where the Al dose is about the half (Figure 5). After adjusting the pH to 6.0 by adding sodium hydroxide the permeability of the membrane pilot went up due to the better flocc forming conditions at this pH. With the better flocculation conditions the Al filtrate concentration decreased to about 100 µg/L. After extending the backflush intervals and lowering the backflush time the permeability decreased slightly. A further increase of pH to 6.3 led to a stable permeability. With this increase in flocculation pH the Al residuals in the filtrate lowered again. A reduction of the Al dose to 1 mg/L (point 15 to 16, Figure 3) did not change the permeability. In the following the recovery achieved up to 92% by operating the pilot at higher hydrogen peroxide backflush intervals and at a higher filtrate flux of 90 L/m²/h. In the mid of June the Al dosing was reduced again which let to a decline of the permeability which could not be stopped even by raising the dosing above the previous value. In this period raw water quality changed. Manganese, iron and chlorophyll contents in the raw water increased. In this situation it is definitely necessary to adopt the flocculation dose to the water quality to stabilize the performance of a membrane plant. However the Al-dose had to be more often changed in the conventional treatment of the flocculation filtration plant. The quality of the filtrate of a membrane plant does not rely that much on the flocculant dose.

TOC Elimination. The TOC-elimination of the process flocculation/membrane filtration is – for the raw water in Roetgen – comparable to the elimination of the flocculation/sandfiltration process, denoted as “plant drinking water” in Figure 5. The differences in removal of TOC are more dependent on the flocculant dose than on the process itself. In the beginning the removal in the flocculation/membrane process was higher when the Al-dose used in this process was about twice the dose used in the conventional treatment. In the end of the period shown when the dose in the flocculation/membrane process is less than in the

Figure 3 Permeability and recovery of the large scale pilot plant

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conventional treatment the TOC concentration in the filtrate of the membrane plant is slightly higher than in the drinking water of the conventional treatment.

**Integrity of membranes**

One of the most important topics in the research program of the WdKA is the monitoring of membrane integrity. Panglisch *et al.* (1998c,d) developed in the former project a relationship between particle concentration in the feed and the maximum membrane area which can be controlled by one particle counter. This relationship was developed by using a pilot plant equipped with an element with cut fibres. These results indicated that monitoring of just one pressure vessel is possible when feeding water after the first filtration step to the membrane filtration plant. These findings were realized in the large scale pilot plant where it is possible to monitor every single pressure vessel as described above.

Figure 6 shows the particle concentrations for 3 sizes in the range of 0.7–3 µm when every pressure vessel is monitored. The switch from one pressure vessel to the other is indicated by a line (green) and the number on the axes “pressure vessel monitored”. PV1 stands for PV100, PV6 for PV600, PV7 for PV101 and PV12 for PV601. It is easy recognizable for all size ranges that elements in PV3, PV6 and PV10 are defect. Particle concentrations for PV11 and PV12 are also significant higher for the size ranges 0.71 and 1–2 µm than the...
background noise measured for the intact pressure vessel. But the concentrations are just about 10–20% of the concentrations measured for the other defect pressure vessels. Glucina et al. (1998) stated that the concentration for the detection of a corrupted fibre should be at least 3 times the noise level, which is a reasonable assumption. If we take this value into account and have a look at the particle concentrations for PV11 and PV12 for the size range of 2–3 µm, we are not able to detect a defect using these values.

The concentration of smaller particles is shown in Figure 7. The defects for PV3, PV6 and PV10 are clearly indicated by high particle concentrations (blue line) too. The particle concentrations for PV11 and PV12 are also significant higher than the noise and just about 10–20% of the value for the other defect pressure vessels. The blue line represents the particle concentrations in normal operation, that means if both filtrate outlets of a pressure vessel are monitored together. The photo in Figure 2 shows that it is possible to shut the valves for every sample point separately. In two subsequent cycles all the valves on one side were closed for one cycle and in the following cycle the valves of the other side were closed. Despite the fact that the filtrate tubes of the elements are connected this procedure may allow us to exclude two of the four elements in a pressure vessel when a defect is not detected on this side. The results are shown in Figure 7, where the green line stands for the particle concentrations of side 1 and the red line for those of side 2. For PV3 the concentrations are about the double for side 2 (no dilution) than for both sides. The concentration for side 1 is comparable to the noise level. For PV6 the defect elements should be on side 2, for PV10 on side 1, PV11 on side 2 and PV12 on side 1 again. When the air bubble test for every element was carried out the following defects were found: 3 defect fibres in one element of PV 3 on side 2, 1 in 1 for PV 6 on side 2, 1 in both elements for PV 10 on side 1, 1 in 1 for PV11 on side 2 and 1 in 1 for PV12 on side 1. These findings are in agreement with the particle measurements shown in Figure 6 and 7. But further on we also found 1 defect fibre in PV10 on side 2 and 2 in 1 for PV 12 on side 2. As a summary of these observations one has to state that defects can be detected by particle counting but there is no correlation between particle concentration measured for defect elements and the number of defect fibres. A closer look to the possible mechanisms when a fibre is corrupted will show that these results can be explained.

The results are summarized in Table 1 and the defect volume flow is calculated by balancing the inlet and outlet particle flows. The defect volume flow can be estimated if it is assumed that the head loss of the flow through a capillary to the broken end equals the transmembrane pressure. This calculation is shown in Figure 8 were it is assumed that the particle concentration in the defect volume flow is the same as in the raw water. If the fibre is broken near the entry where it is fixed in the resin the estimated particle concentration in the filtrate would be about 10 times higher than it would be when the fibre is broken in the middle of the element. If the measured values for the PV30; 60; 401 are compared with the calculation one has to conclude that the fibres in the defect elements are broken rather near the resin. The particle concentrations measured for the PV501; 601 are still too low even if the fibre is broken in the middle of the element. But if the fibres are damaged in a way that the fibre ends are not separated totally the defect volume flow and the particle concentrations in the filtrate would be lower than the calculated values of Figure 8. Further on there might be just holes in the fibres which may be covered by a cake layer formed by the flocs in the raw water. This would lower the defect volume flow again and would also lower the particle concentration in the defect volume flow as well as the particle size distribution due to the retention of the cake layer. The calculated particle concentrations in the filtrate for a cut fibre shown in Figure 8 are the maximum what one would expect. Starting from this maximum everything down to no contribution of the defect regarding the particle concentration in the filtrate may be possible. That may be the reason why there
is no correlation between the number of corrupted fibres and particle concentration in the filtrate.

Conclusions
Using a flocculation/membrane filtration process the treatment of untreated reservoir water is possible at stable operating conditions of the membrane plant. But dosing flocculant less than a certain amount which depends on the raw water quality may lead to a decline in permeability but does not influence water quality very much. It influences water quality in respect of TOC removal which increases slightly with increasing flocculant dose. TOC
removal was in the same order as in the conventional treatment flocculation/sandfiltration.
The choice of a proper pH for flocculation will help to avoid high aluminium concentra-
tions in the filtrate.

Particle counting was used to monitor the membrane integrity. Depending on the raw
water quality and the kind the fibres are corrupted it is possible to detect defect fibres by
particle counting. The possibility to switch particle counting in given intervals auto-
matically from one pressure vessel to the other is advantageous. A correlation between
the number of corrupted fibres and the particle concentration measured in the filtrate could
not be established and may not exist as it was shown by simple calculations of the defect
volume flow and the subsequent discussion of these results.

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Figure 8  Calculated particle concentrations (size 0.7–3 µm) in the filtrate of an element when a fibre is cut
at a certain distance from the entry and comparison with measurements