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Operational Paper

Planning of an ultrafiltration plant with a capacity of 6,000 m^3 h^{-1} for the treatment of drinking water at Roetgen water works

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ABSTRACT

Due to their unique possibilities the relevance of pressure-driven membrane processes in the water technology field increases strongly. Their universal possible fields of application in seawater desalination and waste water treatment, as well as for process and drinking water production explain its enormous growth potential. This trend-setting technology has also become more and more important in Germany. Accordingly, the German WAG Wassergewinnungs- and aufbereitungsgesellschaft Nordeifel is currently building an extension of their existing water work (WW) at Roetgen/Aachen consisting of an ultrafiltration (UF) membrane plant with a capacity of 6,000 m^3 h^{-1}. Furthermore, a second UF stage with a capacity of 600 m^3 h^{-1} for the treatment of the back-wash water of the first stage is being built.

The paper gives an overview of the planning process starting from first pilot plant experiments with small pilots to the ideal design of Germany's largest drinking water treatment plant by means of membrane technology. Further, it shows the benefit of efficient co-operation between a dedicated consumer, an internationally active research and consulting institute, and a well experienced planning agency.

Key words | drinking water treatment, large scale application, pilot plant experiments, planning, ultrafiltration

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INTRODUCTION

The Ingenieurgesellschaft WETZEL + PARTNER (engineering consultants' corporation WETZEL + PARTNER, IWP) is designing an extension of the treatment plant for drinking water (TWA) in Roetgen, North Rhine-Westphalia, Germany, for the Wassergewinnungs- und aufbereitungsgesellschaft Nordeifel mbH (Company for Water Catchment and Treatment North Eifel, Germany, WAG). The extension consists of an ultrafiltration (UF) membrane plant with a production of 6,000 m^3 h^{-1} of drinking water. This makes it the largest membrane plant at present for the purpose of drinking water treatment in Germany. The extension will serve the additional safeguarding of drinking water quality at all times by optimally removing particles including all microbiologically relevant components.

Furthermore, a second UF plant for back-wash water accruing in the treatment process and the construction of an additional drinking water tank with a storage volume of 6,000 m^3 are being planned. The work on the second UF plant is supported by the engineering office Witteveen and Bos from the Netherlands.

The new treatment line in the TWA Roetgen will be innovative and advanced in using membrane technology for the treatment of surface water, not only because of its size. Numerous intensive preliminary investigations were carried out by the WAG's scientific consultant, the Rheinisch-Westfälisches Institut für Wasserforschung gem. GmbH (Rhineland-Westphalian Institute for Water Research GmbH, IWW). The investigations showed that the membrane technology of the TWA Roetgen will be most efficient if flocculated raw water is used. The UF will take place almost at the beginning of the treatment line and not, as commonly employed, as a 'police filter' at the end of the treatment line (Dautzenberg *et al*. 1998, 2001; Hagmeyer *et al*. 2001).

In the preparation and pilot period, a comparison and evaluation of the methods used for pressure pipe and immersed suction membranes were carried out. The results of the comparison and evaluation are of special interest. Both technologies can be rated as comparable for treatment at the TWA Roetgen facility (Urban & Holy 2002), with regard to process engineering and economic considerations. This fact induced the WAG to let both variants be planned in detail and to call for tenders for both. This will lead to increased competition due to the additional competing interests.

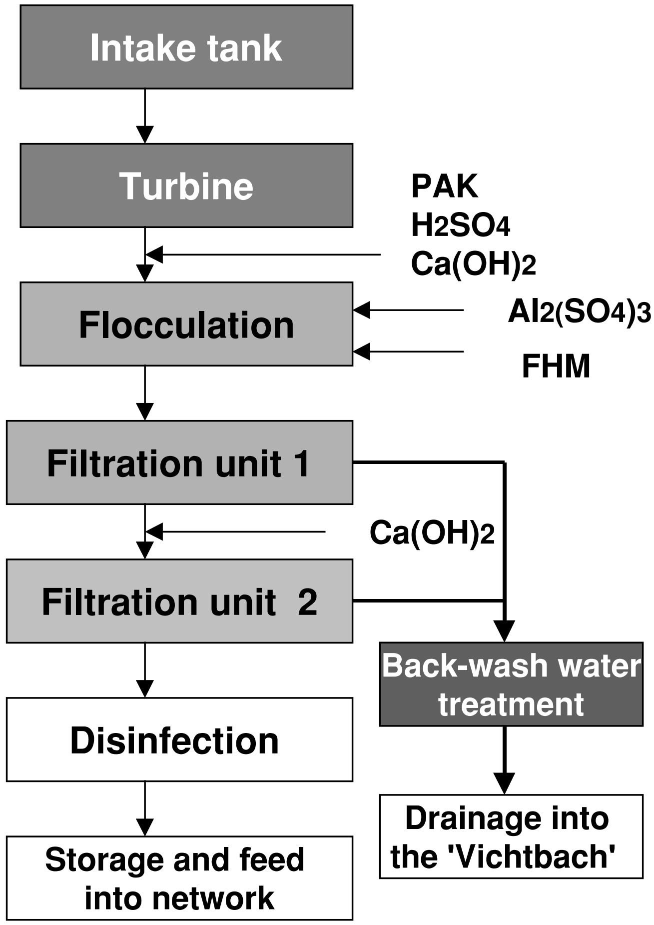

Figure 1 | Process concept of the present TWA Roetgen.

CONDITIONS

Supply situation

The WAG extracts raw water from two drinking water reservoirs, the Dreilägerbach- and Kalltalsperre, as well as from the upper lake of the reservoir Rurtalsperre.

The WAG produces around 40 million m^3 of water per year in two drinking water treatment plants. This drinking water is distributed via the associates WdKA and STAWAG in their service areas to approximately 500,000 inhabitants and several industrial enterprises. The service areas extend from north of the TWA Roetgen across the town and district of Aachen to the district of Heinsberg. It also includes areas in the Netherlands (Vaals and Kerkrade).

The largest treatment plant is the TWA Roetgen with a drinking water capacity of 6,000 m^3 h^{-1}. It is situated at the bottom of the dam of the Dreilägerbachtalsperre. It purifies approximately 32 million m^3 of drinking water annually.

Present concept of treatment at the TWA Roetgen

Figure 1 shows the process concept of the present TWA Roetgen in a flow chart.

The path of the raw water from the Dreilägerbachtalsperre to the TWA Roetgen starts at the intake of the elevated tank. Before being treated, the raw water flows through a turbine, thereby using the available hydraulic gradient for power generation.

The process of drinking water treatment at present implies the following procedural components:

- Optimal dosage of activated carbon filter (the dosage was only envisaged for emergencies and has not been required up to now).
- Adjustment of the ideal flocculation pH-value by optional dosing of lime water or sulphuric acid.
- Dosage of the flocculant aluminium sulphate (alum).
- Dosage of the flocculating agent (FHM).
- Floc formation and aggregation in a reaction vessel with a capacity of 1,700 m^3.
- Floc filtration in a first filtration unit with 13 hydraulically opening, dual-chamber filters of concrete with a filter area of $A_F = 1{,}170\ m^2$ in total. In the first filtration unit, the aggregates formed during floc formation as well as part of the iron are separated to a large extent.
- The dosage of lime water for the adjustment of the pH equilibrium value.
- Filtration in a second filtration unit with eight hydraulically opening, dual-chamber filters made from concrete with a filter area of $A_F = 720\ m^2$. In the second filtration unit, the removal of residual iron as well as the removal of manganese and nitrates takes place.
- Disinfection with chlorine gas and chlorine dioxide.
- Drinking water storage in a two-chamber tank with a total capacity of approximately 3,000 m^3.
- The drinking water flows into the distribution network, according to the natural gradient.
- There are two sedimentation basins, two thickeners and three earth basins provided for the conditioning of the filter back-wash water accruing as a result of the treatment process.

FUTURE CONCEPT: EXTENSION OF THE TWA ROETGEN CONSISTING OF A UF MEMBRANE PLANT FOR THE TREATMENT OF DRINKING AND BACK-WASH WATER

Target

The basis for the planning of the new treatment plant in the TWA Roetgen were the following targets:

- Extensive elimination of organic components from water, especially the reduction of the content of humic substances. This demand implies the lowering of the tendency for microbial 'regrowth'.
- Effective removal of particles for all encountered raw water qualities; an effective retention of particles guarantees an unobjectionable microbiological drinking water quality, and leads to a reduction of the disinfectant required.
- Removal of transient increases in the contents of iron, manganese and ammonium in the raw water.
- Hardening for the improvement of buffer capability.
- De-acidification and adjustment of the pH-value according to the requirements of the drinking water regulations.
- Prophylactic disinfection.

Preliminary investigations and pre-planning

Figure 2 provides an overview of the continuous development of the project since 1995. The first investigation project was to examine whether the extension of the existing drinking water treatment by membrane filtration could provide water of the highest quality in microbiological terms regardless of the raw water quality. Another objective was to find out which membrane type is the most suitable for the TWA Roetgen. According to these objectives, several types of membranes were investigated. During extensive pilot tests several semi-industrial testing plants were tested in different combinations together with the existing treatment stages.

In a second step, a pressure membrane pilot plant with a treatment capacity of approximately 150 $m^3\,h^{-1}$ according to the XIGA concept, which is an horizontal pressure pipe design for ultrafiltration first developed by X-Flow (Blume & Roesink 1998) has been operated since 1999. It was found that UF operation is most stable when fed with flocculated raw water. In close co-operation between the WAG and the IWW different operational conditions were tested and optimised. Simultaneously pilot tests with an immersed suction membrane pilot plant with a treatment capacity of about 100 $m^3\ h^{-1}$ have been carried out for some time. Several testing plants for the treatment of the

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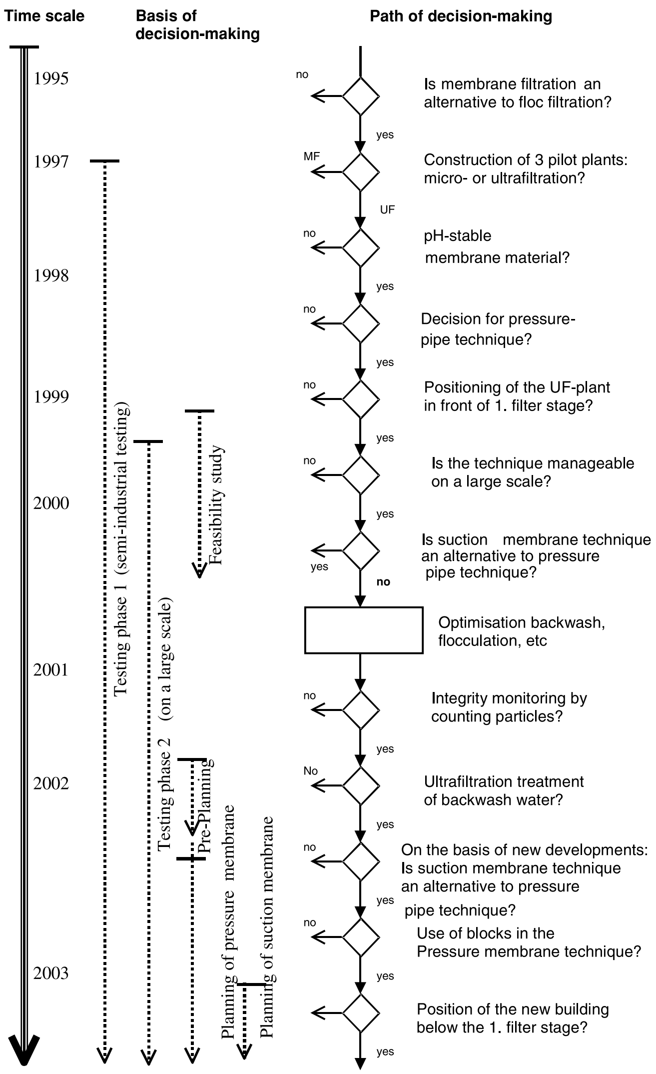

Figure 2 | Overview of the project phases and decision-making in the planning of the extension to the TWA Roetgen (Dautzenberg *et al*. 1998, 2001; Hagmeyer *et al*. 2001; Urban & Holy 2002).

back-wash water of the first membrane stage are also in operation (Dautzenberg *et al*. 1998, 2001; Hagmeyer *et al*. 2001).

In addition to a number of optimisations to the operational scheme, the following two aspects can be regarded as essential results arising from the test phase with direct consequences for the planning of the implementation:

- The advantages of membrane filtration can be used optimally if employed for the filtration of flocculated raw water. Positioning behind the existing floc filter (first filtration unit) is also possible, but less efficient.
- Within an optimised back-wash process, the back-washing of the membrane units can only be carried out with base or acid. This is the case with the pressure pipe technique as well as with the suction membrane technique.

Therefore, regular back-washing with disinfection agents can be omitted. This means that problems which often occur due to the discharge of disinfectant-containing back-wash water no longer occur.

IWP carried out a feasibility study and the planning of a series of possible variants for the treatment of drinking and back-wash water. These variants were compared and assessed in detail regarding process engineering and cost-efficiency.

On the basis of the test results and the planning, the optimised combination of treatments was found for the integration of the UF membrane plant into the existing plant constituents of the TWA Roetgen.

Overview of future drinking water treatment

Future treatment in the new TWA in Roetgen includes the following process operations (see also Figure 3):

- Withdrawal from the existing intake elevated tank.
- Pre-filtration with an automatic back-washing filter for the protection of subsequent membrane units against larger particles; these larger particles can lead to damage of the membrane fibres. The mesh size of the pre-filters will be adjusted to the particular membrane type.
- The back-wash water from the first UF stage will be treated in the back-wash water UF treatment plant and then fed to the raw water in front of the treatment line.
- Within the future treatment concept, it will be possible to use powdered activated carbon (PAC) dosing if pesticides or other contaminants enter the raw water, for example by an accident in the catchment area of the reservoir. The adsorbed contaminants will then be removed by membrane filtration together with the carbon particles.

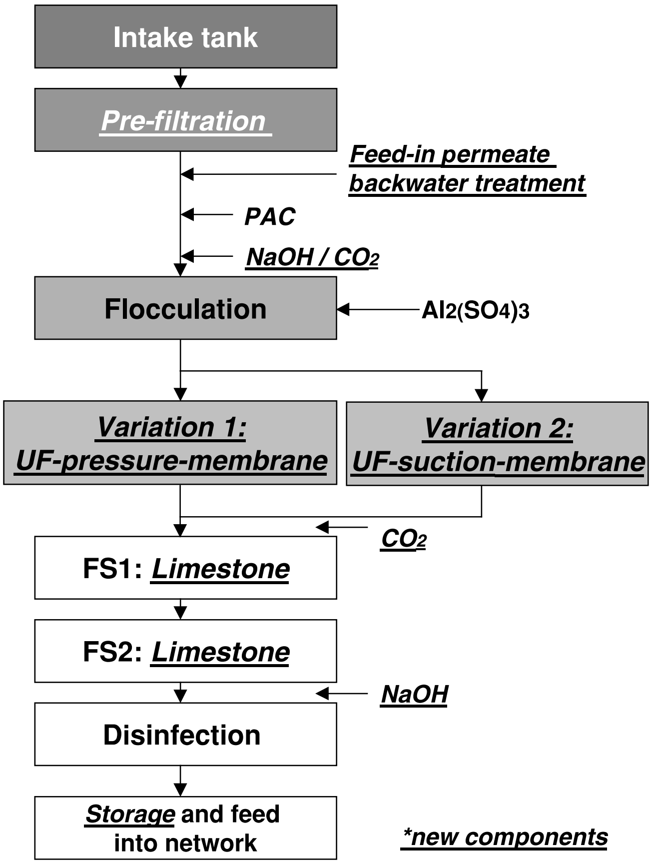

Figure 3 | Flow chart of the future drinking water treatment concept.

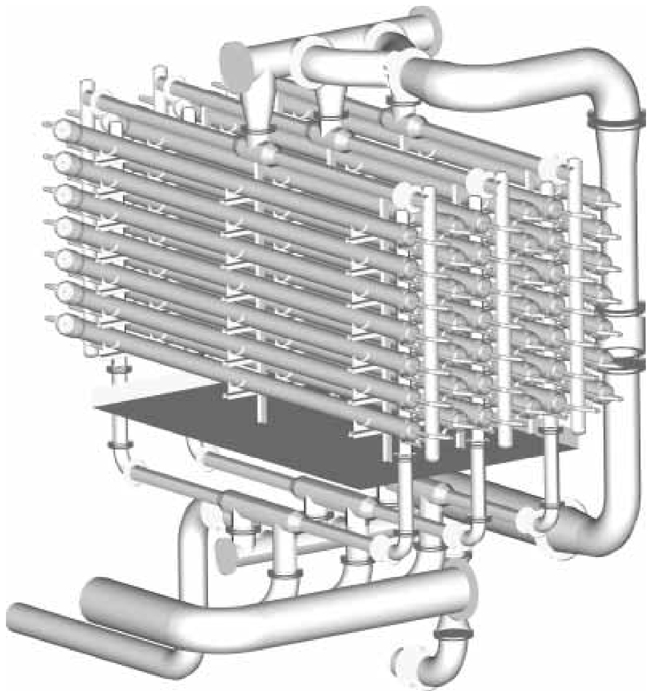

Figure 4 | Block for the pressure membrane filtration in the TWA Roetgen.

- According to requirements, the ideal pH level is adjusted before adding the flocculant. The adjustment is carried out with either sodium hydroxide (NaOH) or carbon dioxide (CO_2).
- Flocculation: As flocculant, aluminium sulphate ($Al_2(SO_4)_3$), polyaluminium chloride (PACl, pre-polymerised) and iron (III) chloride ($FeCl_3$) are available options. The rapid and homogeneous mixing of the flocculant is done with a dynamic blender with controllable energy use.
- For the ultrafiltration of the flocculated raw water, two variants of the process are being planned:

Variant 1: UF by means of pressure pipe membranes

Twelve blocks (see Figure 4) with a maximum gross treatment capacity of about 560 $m^3 h^{-1}$ for each block. Using the pressure pipe option, the flocculation only takes place in the two transportation pipelines between the flocculant dosing and mixing unit and the UF plant (pipe flocculation with a minimal reaction time of one minute).

Variant 2: Ultrafiltration by means of suction membrane

For the use of suction membranes, ten streets with a maximum gross treatment capacity of about 650 $m^3 h^{-1}$ are being planned. It is possible to use the existing reaction vessel for flocculation in the suction membrane plant. This requires at least 15 minutes' reaction time in the vessel.

- The filtrate of the UF plant will flow to the existing filter stage 1. At the intake of the filter stage 1, CO_2 could be optimally dosed, in order to obtain a significant hardening of the drinking water. After limestone filtration residual CO_2 will be removed in the final chemical de-acidification with NaOH.
- Filtration with limestone (calcium carbonate) will take place in the existing filters of the first and second filter stages. There will be 13 open concrete filters available to be filled with limestone in the first stage, and eight in the second filter stage. The

Table 1 | Comparison of the essential characteristics of the contemplated variants for membrane filtration at the TWA Roetgen

Characteristics of pressure pipe technique	Characteristics of suction membrane technique
The specific flow of filtrate is higher, therefore the necessary membrane area is smaller (approx. 90 l m^{-2} h in comparison to approx. 55 l m^{-2} h for the suction membrane)	The expenditure for the procedual periphery is smaller and therefore it is more cost saving
During normal operation it is not necessary to use a pumping station for the production of raw water or filtrate. But in exceptional cases, there has to exist a pumping station for raw water, which will be connected in case of demand	A pumping station for drinking water is not necessary, because the pressure from the reservoir is sufficient to feed the flocculated raw water into the membrane basins. However, the filtrate of the suction membrane needs a permanent pressure increase, because the siphon principle cannot be realised economically due to topography
The possibility to use pressure pipe membranes shows a more positive energy balance altogether: It is not necessary to increase the pressure for the transport of filtrate and permanently aerate the basins	Fewer chemicals are necessary for the back-washing process. The utilisation of chemically pure back-wash water after the treatment (see section on back-wash water treatment), leads to a slightly higher yield for the entire plant (99.8% in comparison with 99.3% for the use of pressure pipe membranes)
The entire filtration takes place in enclosed vessels. No open water levels arise. This is an advantage for the building technology (airing, dehydration)	Further measures such as the covering of basins are sensible, in order to capture the humid air and transport it outside the building
The degree of concentration on the raw water side is lower, because solids on the feed side are removed from the process with every back-washing (advantageous when defects occur in the membranes, because less concentrated raw water infiltrates on the permeate side)	According to existing, evaluated operational experience from reference plants, there are fewer defects in membranes to be expected when suction membranes are employed, because of a more solid construction
	When searching for leakage and during substitution of elements, the handling of membrane elements is very simple. In general, less expense is expected for the maintenance and the repair of membranes when using suction membranes

volume of the filter material will be approximately 3,000 m^3 in total, corresponding to a reaction time of at least 30 minutes. The water from the reservoirs, which has already been filtered by membranes, will be hardened and de-acidified by limestone filters. If required, the residual iron and manganese will be removed biologically in the limestone filters and nitrification will take place.

- Before the drinking water is fed into the storage tank, it will be prophylactically disinfected with chlorine dioxide, in order to protect the distribution net.
- Before being finally supplied, the drinking water will be intermediately buffered in two existing chambers, each with a volume of 1,500 m^3, and two new chambers, each with a storage capacity of 3,000 m^3.

Comparison of the variants of ultrafiltration

During preliminary investigations and pre-planning, the two procedural variants of UF—pressure pipe membrane and immersed suction membrane—were tested and evaluated regarding operational, and economical aspects and process engineering.

In Table 1, the two variants are compared with regard to installation *in a new building*. Several of the characteristics listed are specific to conditions at the TWA Roetgen.

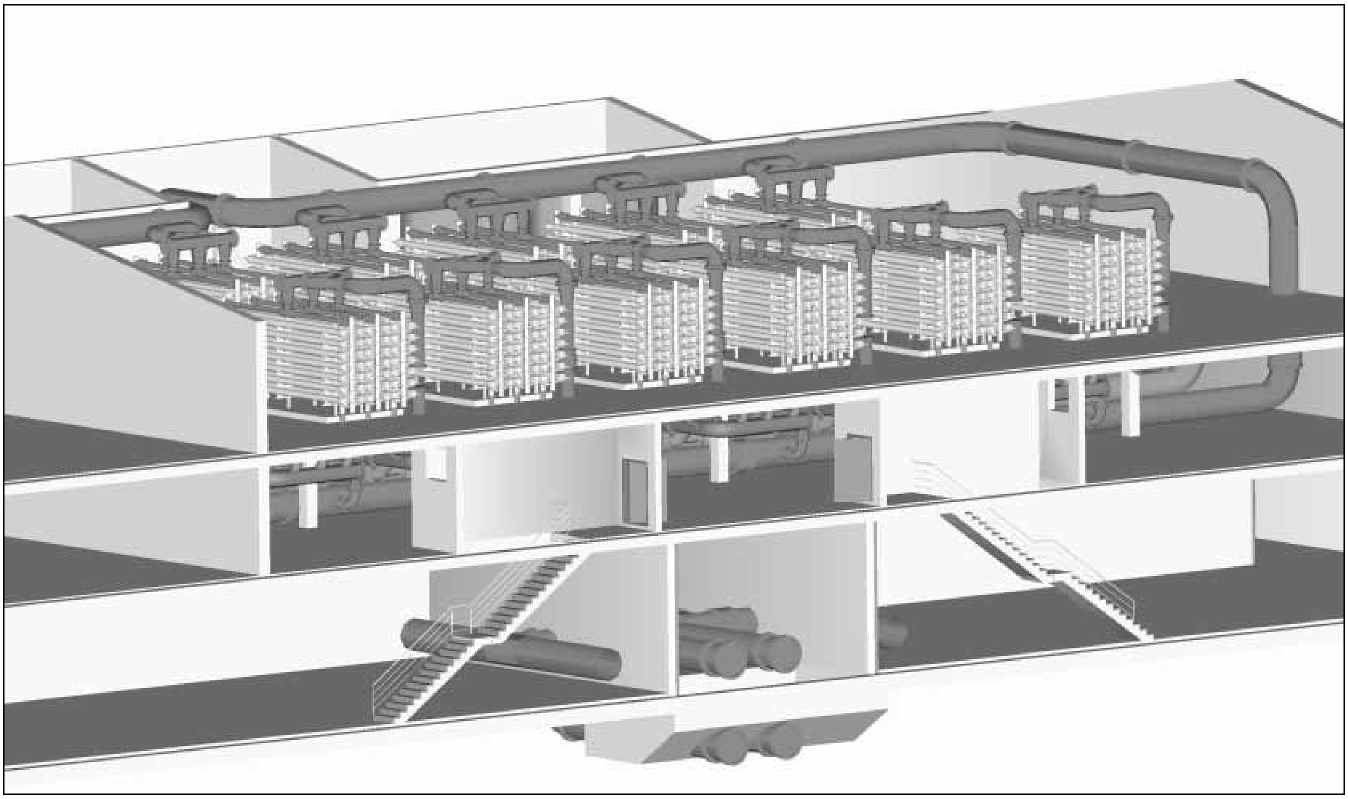

Figure 5 | Design draft for the new part of the building of the pressure pipe versions below the new drinking water storage.

Within the scope of planning, the utilisation of the existing filtering basins for the deployment of suction membrane cassettes was also examined, in order to reduce the costs for the construction unit. In this case, numerous temporary solutions would be needed to achieve the necessary treatment capacity during the reconstruction period. Therefore, the construction phase would extend because of the additional co-ordination expenditure. Furthermore, filter stage 1 could not be used for the limestone filtration. These factors and their economic consequences preclude the obtainable savings. Therefore, this variant was dismissed.

According to these procedural considerations both techniques can be regarded as equivalent for the planned application at the TWA Roetgen. In order to decide on one variant during the conceptual phase, the alternatives were planned and compared in more detail. These considerations show that in this special case the space requirements for both variants are about the same and that the costs calculated for the construction unit are also comparable (see Figure 5 and Figure 6).

The higher costs for the membranes of the suction membrane variant are balanced by additional costs for the procedural periphery of the pressure pipe technique. However, the detailed cost calculation demonstrates that the two variants for operation in the TWA Roetgen are similar in cost.

In summary, no crucial advantage could be determined for suction or pressure membrane technology on the basis of a procedural and economic evaluation. Therefore both technologies are excellently suited for integration into the drinking water treatment process of the TWA Roetgen.

Accordingly, WAG has assigned IWP to plan *both* variants to the stage of tendering. This dual planning encouraged competition for tenders from membrane manufacturers and engineering companies. The additional

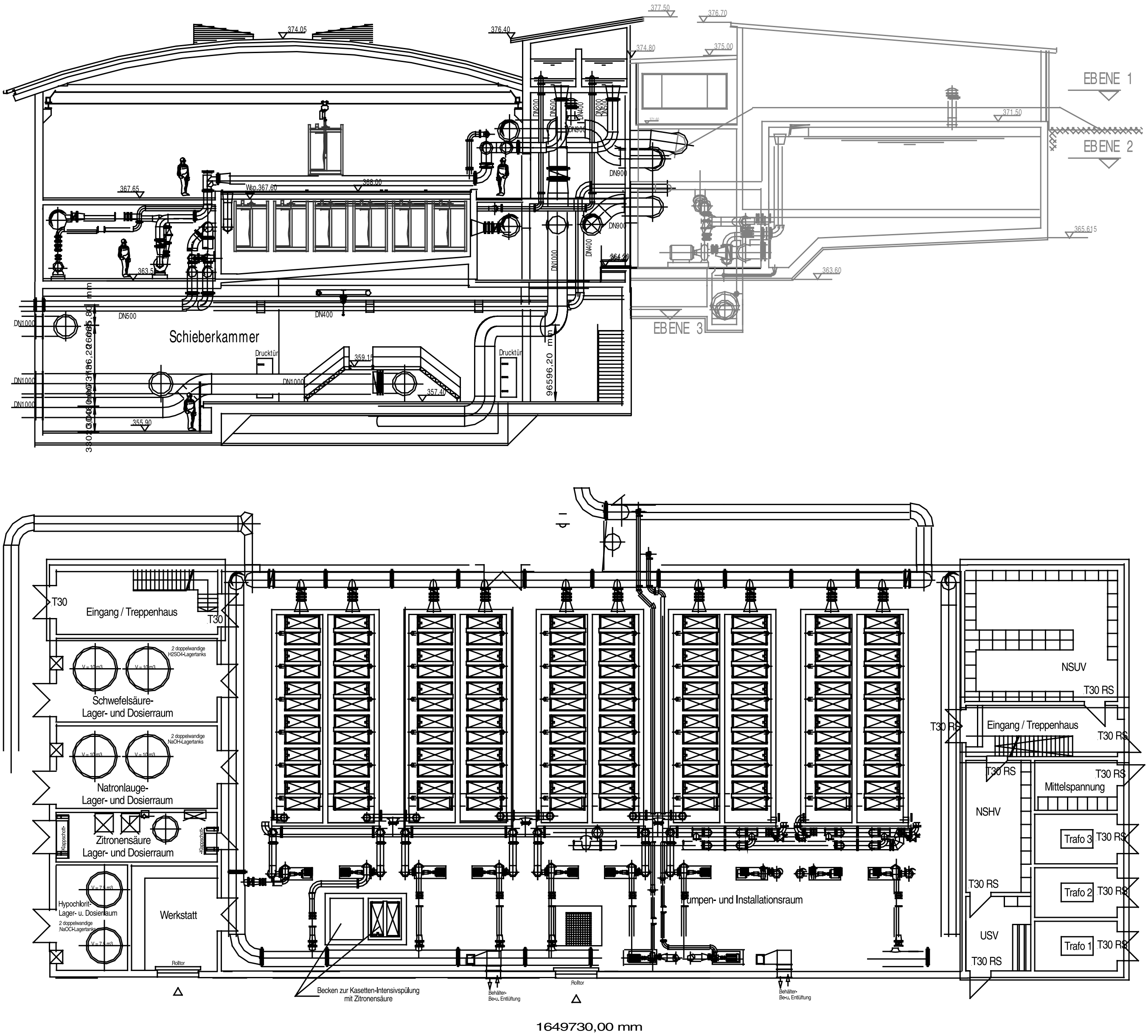

Figure 6 | Ground sketch and sectional view of the new part of the building showing the suction membrane variant above the new drinking water storage facility.

costs for planning both variants will surely be balanced by competition.

Back-wash water treatment

The objective for planning back-wash water treatment was the re-use of treated back-wash water to a large extent by its re-issue into the raw water. In this way, the small river used for discharging will not be hydraulically overstressed and the raw water resource will be saved. Furthermore, it is favourable to integrate and optimise the use of existing components in the process.

A crucial planning task involved addition of the treated filtrate from the back-wash water treatment into the raw water destined for treatment. Due to licensing requirements, an additional UF plant for the treatment of chemical-free back-wash water is intended.

In the future treatment process, chemical-free and acidic and caustic back-wash water will accumulate separately. The concept for back-wash water treatment provides the following:

- the chemical-free back-wash water will be treated in a second UF plant. The filtrate, which will have drinking water quality, is re-fed into the raw water. The concentrate of the second UF will be treated further in two existing sedimentation basins and in the thickeners.
- Initially, the acidic and caustic back-wash waters of the membrane back-washing process will be collected and neutralised, deposited into an existing sedimentation tank, and subsequently discharged into the receiving water. The amount of back-wash water containing chemicals will be so small that the total amount to be discharged will obviously be smaller in comparison with the present floc filtration procedure.
- A diagram of the back-wash water treatment plant with several treatment paths for chemical-free and acidic/caustic back-wash water is given in Figure 7.
- The dimensioning of the components of the back-wash water treatment plant will differ slightly from the UF treatment of drinking water due to the procedural implementation. On the whole, the principle of the process designed for the back-wash water treatment is identical.

The treatment of back-wash water will be conducted as follows:

- All chemical-free back-wash waters are to be collected and stored in the interim in an equalising tank consisting of two separate chambers. The chemical-free back-wash waters are to be transported from the buffer equalising tank to the back-wash water UF plant (SW-UF).
- The chemical-free back-wash water will be treated in the SW-UF. The utilisation of either immersed suction membranes or pressure pipe membranes is also conceivable for the treatment of back-wash water.

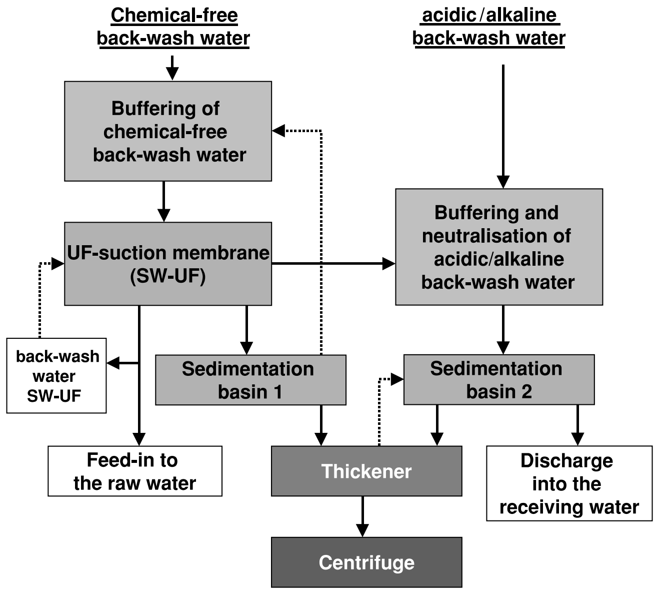

Figure 7 | Flow chart of the planned back-wash water treatment.

- The plant will consist of three blocks or streets with a treatment capacity of approximately 200 $m^3\ h^{-1}$ each.
- The filtrate of the SW-UF will be fed mainly into the raw water feeder, and part thereof will be stored temporarily in separate back-wash water tanks for the back-washing of the SW-UF.
- The concentrate of the SW-UF will be transported to the existing sedimentation basin and treated further in sedimentation basin 1.
- The acidic and caustic back-wash waters of the drinking and SW-UF will be temporarily buffered and neutralised in a neutralisation basin. The water will be mainly neutralised by mixing of acidic and caustic back-wash water. Furthermore, dosing of acid and base for a specific pH value adjustment will be possible. The neutralised, chemical-containing back-wash water will be transported to the existing sedimentation basin 2, where it will undergo further treatment.
- The existing sedimentation basins will be operated as follows: The concentrate of the suction membrane plant in sedimentation basin 1 and the neutralised back-wash water in sedimentation basin 2 will be treated. The clear-water from sedimentation basin 1

(concentrate from suction membrane) will be transported back into the equalising tank, and the clear-water from sedimentation basin 2 (neutralised back-wash water) will be discharged into the receiving water.

- In the existing thickeners, the sludge liquor of the two sedimentation basins will be thickened and finally dehydrated to a large extent using a mobile centrifuge. The clear-water from the thickeners will be re-transported to sedimentation basin 2 and thus finally discharged into the receiving water.

The future SW-UF at the TWA Roetgen will form a functional unit with the existing plants of the back-wash water treatment facility. Drinking and back-wash water treatment will therefore take place in spatially and functionally separated units. The new back-wash water treatment plant including all basins as well as storage and dosage stations necessary for the back-washing of the suction membrane plant will be integrated into a new building. An overview of this building is provided in Figure 8.

Monitoring the integrity of the membranes

For the monitoring of treatment efficiency and the integrity of membranes, particle counting will be applied (Panglisch *et al.* 1998). The concentration of particles and the turbidity in the filtrate of the membrane filters will be measured and controlled continuously.

A reduction in the raw water particle concentration of four logarithmic units was determined as a target value for the reduction of particles in the treatment of drinking water. In comparison with worldwide requirements, this value is far below the most stringent critical limits discussed presently. The approach to this level signifies to the operating staff the necessity to diagnose and repair defective membrane fibres. Therefore, this value represents a threshold value and should not be seen as an absolute critical limit.

Correlating to an average concentration of particles in the raw water of about 10,000 ml^{-1} with dimensions of 2–20 μm, the reduction of four logarithmic units corresponds to a reduction of the absolute concentration of particles to 1.0 P ml^{-1} (2–20 μm) in the permeate of the drinking water UF plant.

It is also relevant to consider which membrane surface(s) will be controlled with a particle measuring device. In the new TWA Roetgen, the observance of the target value will be monitored in:

- the collecting pipe of the permeate and
- the permeate outlet of each membrane block or membrane street.

The control system will constantly calculate the reduction achieved in relation to the number of particles in the raw water. It will also monitor the data regarding an adjustable warning value and a target value.

In the manner described above, all membrane blocks or streets will be monitored permanently and automatically. In the case where retention of particles is suboptimal, the offending blocks will be reported to the user in order to fulfil the demands set for the new treatment plant.

Besides the monitoring of the membrane integrity, procedural conditions for the detection and localisation of defective membrane fibres or packing will be created. For this purpose, a graded system encompassing the measurement of particles and turbidity will be constructed, in order to analyse:

- particular rows of pressure pipes and particular pressure pipe or suction membrane cassettes
- particular membrane units.

SUMMARY AND PROSPECTS

The present plans for an extension of the TWA Roetgen, in this case comprising an ultrafiltration plant, show an ideal case of co-operation between:

- a dedicated consumer, guiding the planning intensively with its specialised knowledge and awareness of specific marginal conditions
- an internationally active institute, with more than 15 years experience in the field of membrane technology, which offers both competent consultation and scientific support, and

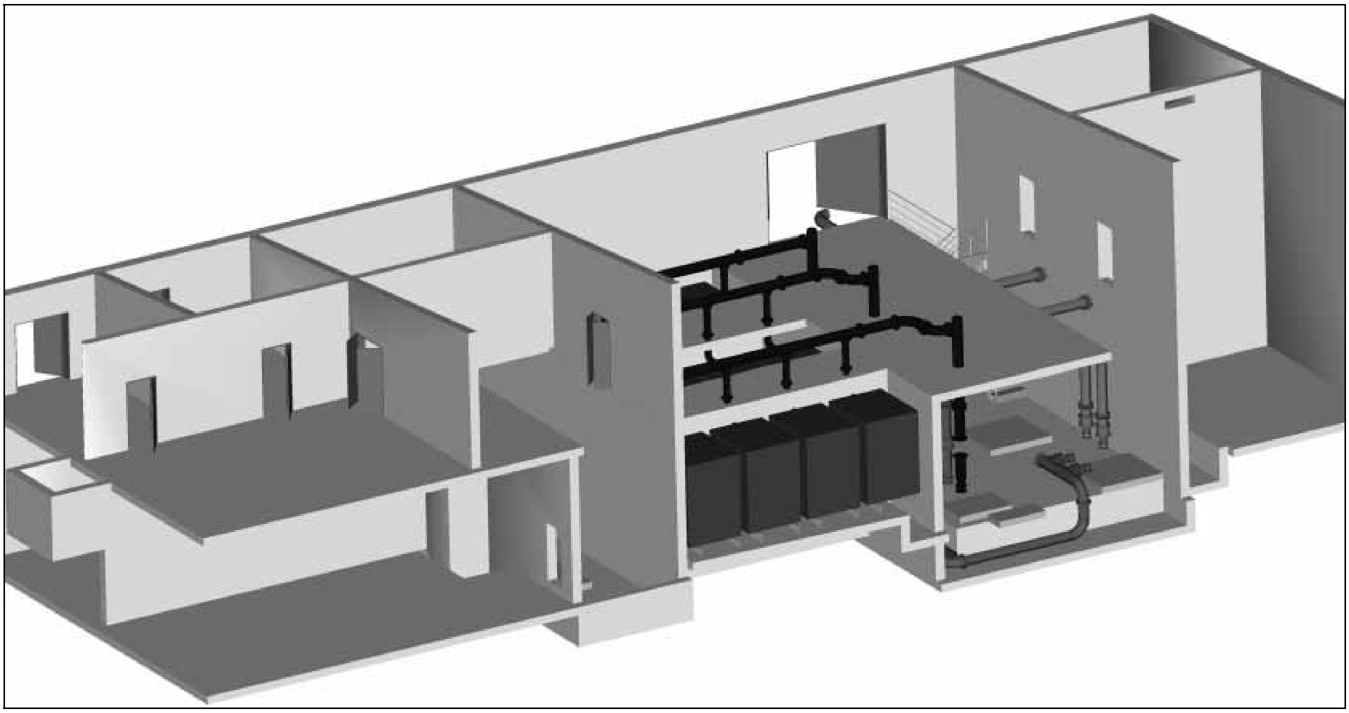

Figure 8 | Model of the new building for the treatment of back-wash water.

- a planning agency with wide-ranging experience in the planning of treatment plants, particularly in the field of membrane technology.

The implementation of preliminary experiments, and the possibility to immediately analyse parameters relevant for the planning at the experimental plants effectively allows ideal planning tuned to the application and without ‘expensive safety margins’.

The new TWA is presently the largest plant planned in Germany for the treatment of drinking water by means of membrane technology. Based solely on its capacity, it is innovative and advanced. Of great interest is the detailed comparison between the technologies of the pressure pipe technique and immersed suction membranes, which is underpinned by pilot plant experiments on a half technical scale.

Only with consideration of the different specific conditions, and with a complete knowledge of all potential process technologies, it is possible to develop an ideal design for certain applications. In the case where several membrane filtration techniques are rated as equivalent, a dual-planning scheme may lead to the most economical variant.

Actually, the authorities agreed to the planned concept for the extension of the TWA Roetgen. The advertisement was accomplished in the first quarter of 2004. The completion of the treatment plant according to its new concept is foreseen for the end of 2005.

Note that no detailed cost estimations can be published due to the forthcoming tendering procedure. It is however reasonable to specify that the specific costs for the extension to the TWA Roetgen will be below 10 €-cent m^{-3} drinking water. This has been calculated for the invested capital and the operating costs of the *entire* treatment envisaged.

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