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Large-Scale Biological Nitrate and Ammonia Removal

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ABSTRACT

In order to treat water containing nitrogen in excess of the European Drinking Water guideline, an innovative large-scale biological, nitrogen-removal process bas been used. After extensive pilot-scale testing and a first ful-scale (80 m3/h) demonstration at Eragny (France), a 400 m^3/h installation, serving about 50000 people, was built at Guernes-Dennemont, near Paris. The raw water source is a combination of percolation from agricultural plains and river bank infiltration, and contains both nitrates and ammonia.

The plant consists of two fixed-bed biological reactors in series. An anoxie filter, using ethanol as a carbon source for heterotrophic bacteria, removes nitrates at filtration rates up to 10 m/h. The denitrified water is then polished on an aerated two-layer filter, packed with activated carbon and sand. Excess carbon from the first stage, together with reduced nitrogen (ammonia and nitrates), is oxidized at this stage before ozonation of the water.

Design data and operational performance are given for total nitrogen (NO_3 and NH_3). total organic carbon (TOC) and chlorinated hydro-carbons. A specifie dosing method for biodegradable carbon was developed to monitor the efficiency of the post-treatment. Special attention was paid to (a) nitrate control through improved backwash, and (b) reducing the potential for bacterial contamination and aftergrowth in the distribution network.

Key words: Fixed-film reactor; biological filtration; denitrification; nitrates; nitrification; ammonia; organic solvents; biodegradable organic carbon.

INTRODUCTION

In 1980, the European Guideline on Drinking Water (EEC 80/778) fixed the standards for nitrogen in potable water 25 mg/1 of nitrate and 0.05 mg/l of ammonia (NH_3) were recommended, but levels twice as high for nitrates and ten times as high for ammonia are tolerated[1].

Because of the widespread occurrence of nitrates in groundwater[2,3], these quality requirements initiated intensive research on nitrogen-removal methods. Different techniques, based on physico-chemical or biological principles, were investigated and compared for technical and economical feasibility[4]. Membrane separation is possible[5], but costs have been prohibitive for full-scale nitrogen removal applications[6].

The objective of this paper is to present the pilot-scale investigations that led to the largest drinking water denitrification plant (to date) incorporating both anoxie and aerated biological filters.

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ION EXCHANGE

Ion exchange is a widely-applied process for industrial water treatment, but health considerations regarding the release of undesirable substances by synthetic resins initially retarded the application of this technology[7]. Following intensive pilot-scale investigations, improvements in resin quality and specificity have led to full-scale applications[8,9,10]. The highly-concentrated waste stream from resin regeneration requires special attention, even though biological treatment as been proposed for its elimination[11].

The physicochemical method based on ion exchange can provide an attractive alternative, especially for small and average-size facilities. The nitrates eliminated from the water are concentrated into effluents containing regeneration salt, which can be released into a host environment having a sufficient flow rate for the impact of the effluent to remain negligible. The installation of such a facility can therefore only be contemplated in a coastal area or in the immediate vicinity of large receiving waters or sewers.

The first plant, which treated 3200 m3/d, was built at Binic in the western region of France. Concentrated liquors are discharged to the sewage-treatment works. situated in the vicinity of the denitrification plant, which accepts 55 m3/d of resin-regeneration liquor - representing 450 kg of NO_3 and 516 kg of Cl[8]. In France, for many years the possible release of toxic or undesirable compounds by the synthetic-resin ion-exchange system restricted the process. This fact explains why the first French potable water denitrification unit was based on the heterotrophic biological approach.

BIOLOGICAL DRINKING WATER TREATMENT

During recent years, biological treatment of drink-ing water bas increased in popularity for the removal of a variety of compounds[12,13], due to its low cost and reduced health and taste impacts[14,15]. Fixed bacteria on filter grains easily adapt to biological methods, compared with conventional drinking water techniques[16]. Autotrophic bacteria can degrade nitrates without requiring an outside carbon source[17], but their reaction rate is low due to the slow growth rate of autotrophic organisms. Their attachment on to surfaces led to the full-scale application of this process[18], but further studies using fluidized carriers for intensified reactions are presently being carried out[19,20].

Heterotrophic denitrification is a well-known process in the advanced biological treatment of wastewaters[21]. By adding a carbonaceous substrate, bacteria are encouraged to grow, using the oxygen bound in nitrate for their respiration[22]. Even though initial problems occurred during early development of the process[23], different fixed-film systems were developed for high-quality effluents (water re-use) and total nitrogen removal, using fluidized beds[24,25] or immerged granular media[26]. Interest and research in heterotrophic biological nitrate removal for drinking water remains active because of the simplicity of the process and its similarity to conventional water filtration[27]. This technology is now largely applied in several full-scale installations[9,28,29] which differ in support medium, direction of flow and backwashing techniques.

Because carbon is added to the drinking water, and the growth of heterotrophic bacteria is enhanced, these processes rely on an efficient polishing process to re-establish the original quality or improve the final waterquality.

Aerated filters degrade soluble substances and retain particulate pollution and bacteria in one unit[30].

The application of this process to wastewater treatment has estab-lished its purification potential[31], and the reliability of the process has been proved by a number of large-scale installations[32] in both municipal[33] and indus-trial applications[34]. Their efficiency has been tested as a pretreatment step in the production of potable water from highly-polluted surface waters[35]. The attachment of specialized bacteria on the filter grain, as well as the highly-aerated environment, favours nitrification[36]. Optimization and modelling of these aerobic filters showed the interest of downflow operation and counter-current aeration[37].

PILOT-SCALE STUDIES

The aim was to evaluate the biological removal of both nitrate and ammonia from groundwater.Whereas groundwaters increasingly exhibit high nitrate levels[2], ammonia is mostly found in surface waters[15], and nitrification of river waters is now a common practice[14,40]. However, it is rare that both nitrogen species are present in the same source of water. The wells of Guernes/Dennemont, situated about 50 km west of Paris, supply an industrial and residential area of about 50 000 people. The ground-water is fed by percolation from a highly-cultivated plain and by riverbank infiltration of the Seine.

The concentrations of nitrate and ammonia were close to the EC Guidelines, and the absence of an alternative source made it necessary to provide treatment in anticipation of further groundwater nitrogen enrichment.

The pilot-scale plant was based on earlier studies[8], and a flow diagram is shown in Fig. 1. Two downflow columns in series simulate an anoxie and an aerobic filter. Nitrate and ammonium salts are added to increase the concentration up to future design levels (65 mg NO3/l and 3.5 mg NH_3/l), and the loadings can be varied by changing the influent concentrations or the feed rates using variable-speed pumps.

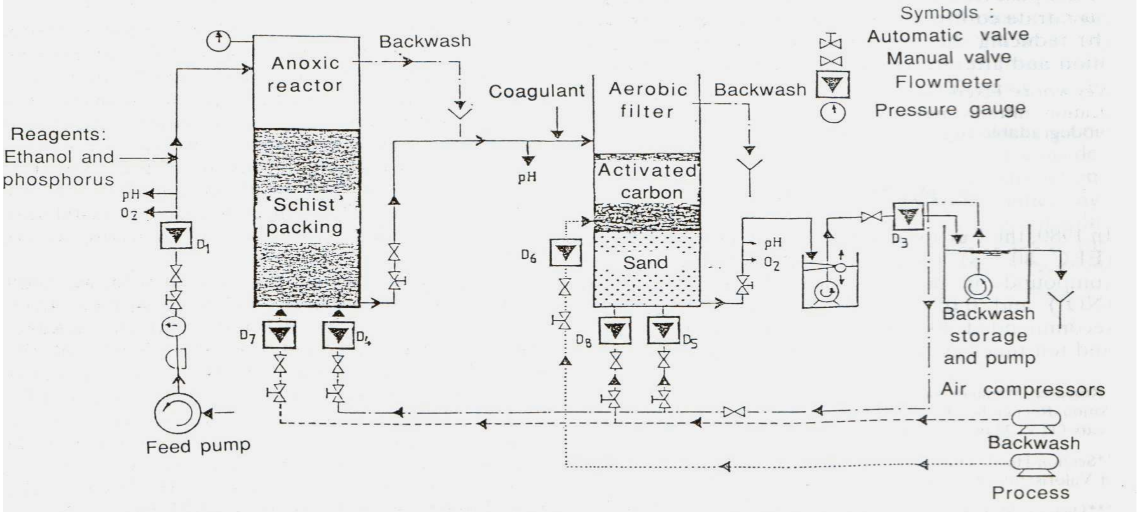

Fig. 1. Flow diagram of nitrogen removal pilot plant

The first reactor is packed with a mineral medium, i.e. heat-expanded 'shist' (a form of shale). The principle of the Biodenit process is based on conventional sand filters, where the water flows downwards under slight pressure on a mineral medium. The heterotrophic bacteria attach to the granular material because of its high immobilizing characteristics, i.e. large specifie surface and high macroporosity; this material has a low density and a good resistance to abrasion. An expanded clay having grain sizes of 2-5 mm was selected, favouring bacterial adherence and limiting head loss.

A polishing treatment is required downstream from the denitrifying filter, since the Biodenit effluent contains no dissolved oxygen (DO), and the bacterial metabolisms easily produce biodegradable organic carbon. The water is polished on an aerated, two-layer, sand and activated carbon filter before ozonation. The potential of biological two-layer filtration for micropollutant and ammonia removal had been demonstrated on large scale without aeration[40], but oxygen becomes limiting at higher substrate concentrations. Air is injected into the middle of the filter at the bottom of the carbon laver, and coagulant can be dosed into the filter feed to increase solids retention. Dissolved oxygen and pH can be measured before and after each reactor. Treated water is stored and used for backwashing, which can be fully automated using pneumatic valves.

DENITRIFICATION RESULTS

In order to obtain a balanced biological growth, phosphorus must be added in addition to the carbon source. The carbon substrate is ethanol - a product that bacteria can metabolize and that is non-toxic. Acetic acid is also allowed by the French Health Council, but the corresponding biomass production (from its degradation) would be higher. The ethanol is 'denaturized' (by the supplier) with sulphuric acid to the extent of 4% in volume.

To calculate the substrate needs, the following equations are used:

$$\text{ethanol} = C = [\Delta - NO_3] \times 0.475 + [O_2] \times 0.55$$
$$\text{phosphorus} = P = [\Delta - NO_3] \times 2.26 \times 10^{-3}$$

where $[\Delta - NO_3]$ = nitrate removal rate (mg/1)
$[O_2]$ = dissolved oxygen in raw water (mg/1)

The influence of the addition of ethanol on elimination profiles in the anoxie reactor is shown in Fig. 2.

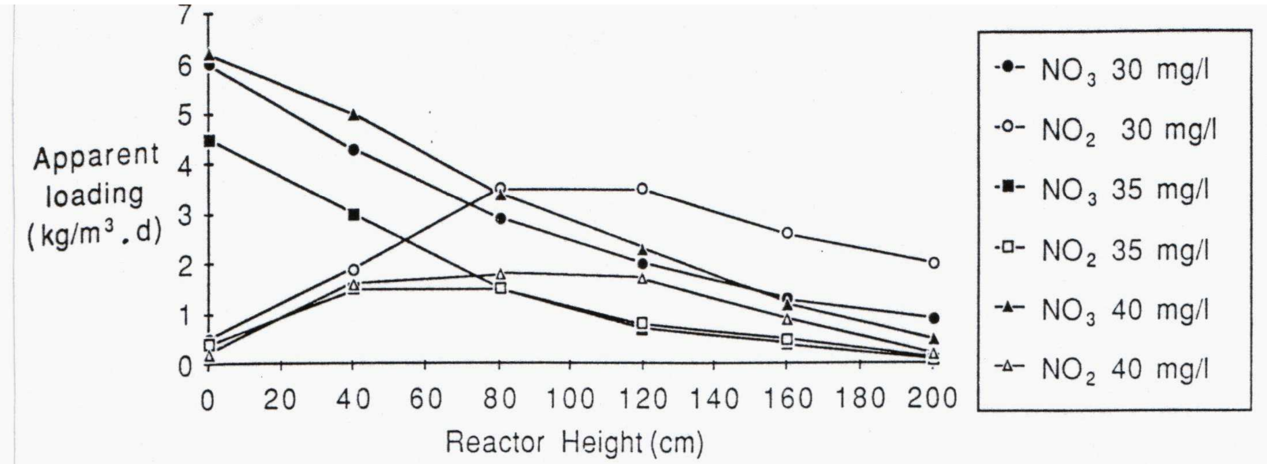

Fig. 2. Profiles of nitrite consumption and nitrate apparition for different ethanol dosages (mg/l) **at influent temperatures <14°C and dissolved oxygen 2 < DO < 4 mg/l**
Loading (kg/m³.d) = Velocity (m/h) × Concentration (mg/l) × 0.024/Bed height (m)

For the influent concentration of 65 mg/1 NO_3 and a filtration rate of 8 m/h, low residuals of nitrates are reached after a bed height of 2 m. The ethanol requirement for these conditions is about 30 mg/1, with an influent DO concentration of about 3 mg/1. However, at lower temperatures, nitrite appears as an intermediate stage if the carbon source is added at the stochiometric rate. Even though residual nitrates are similar for two different ethanol additions in excess of the minimum, residual nitrites are much lower for higher carbon dosings.

The resulting removal rate, when the nutrient requirements are met, is shown in Fig. 3.

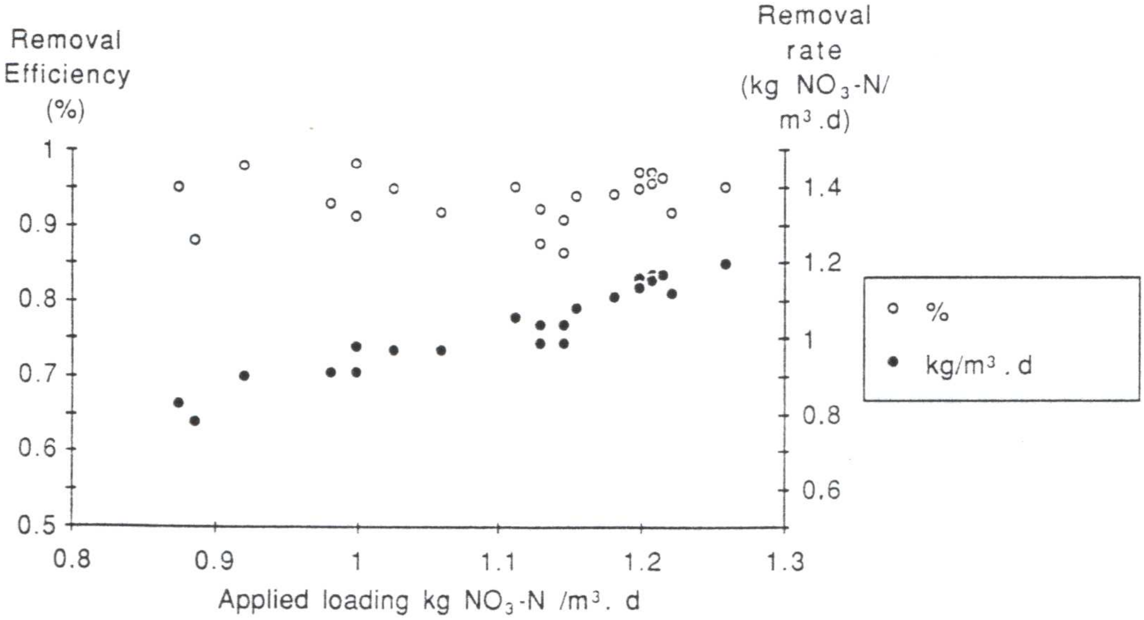

Fig. 3. Nitrate removal efficiency and elimination rate on a media bed of 2.5 m at a filtration velocity of 8 m/h

The removal efficiency is constant, and the complete elimination of nitrates can be achieved up to loading rates of 1.2 kg NO_3-N/m^3.d. For the design concentration of 65 mg/1 NO_3, this corresponds to a filtration velocity of 8 m/h on a filter bed height of 2.5 m.

When the filtration velocity was increased to 10 m/h, removal rates were less stable and nitrate breakthrough occurred.

The resulting nitrogen residuals after denitrifi-cation, for different reactor retention periods, are illustrated in Fig. 4. Complete removal of nitrate and nitrite residuals below the guideline can be attained at an empty bed contact period of 20 mins for influent concentrations above 70 mg/1 NO_3-N.

For lower hydraulic retention periods, residual values of both nitrate and nitrite increase, and the higher the feed value, the higher the effluent concentration.

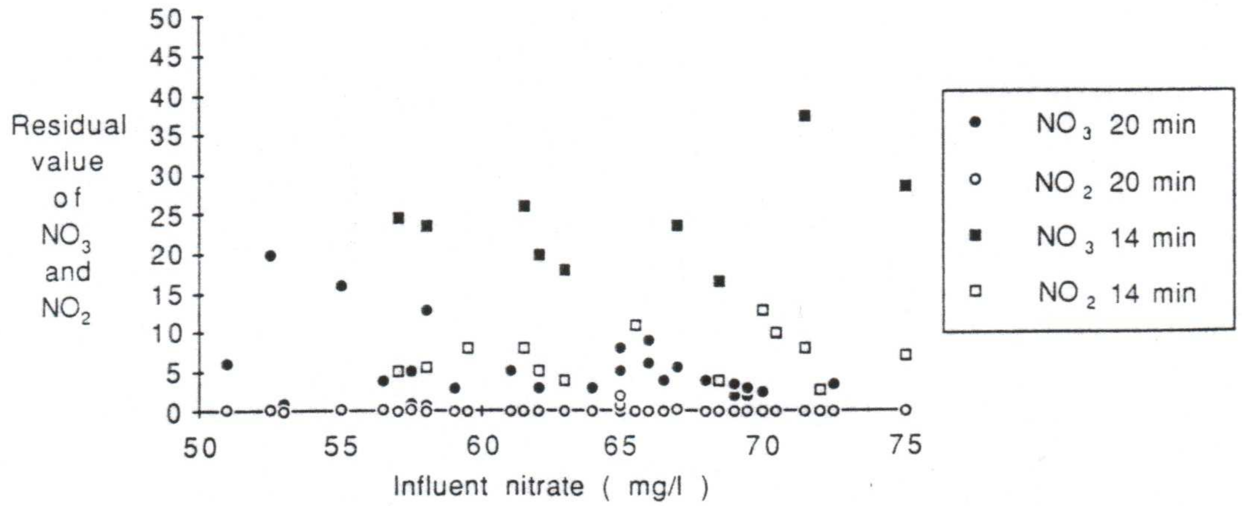

Fig. 4. Residual nitrite and nitrate concentration (mg/l) **dependent on influent nitrogen at two different empty bed contact periods**

NITRIFICATION PERFORMANCE

About 1 mg of amm.N is eliminated through biological uptake by heterotrophic bacteria in the anoxic filter. Non-aerated gravity filters can elimin-ate 1.5-2 mg/1 of ammonia. depending on the influent DO concentration[14,40].

Since no DO is present in the water after denitrification, the water has to be re-aerated.

Combining aeration and filtration leads to a compact process with no oxygen limitations for the removal of high concentrations of ammonia and excess carbon.

A layer of aerated activated carbon (a) removes carbonaceous pollution biologically, (b) saturates the effluent with DO, and (c) eliminates micropollu- tion that is often associated with nitrates. A layer of non-aerated activated carbon acts as a primary filtration process, and finally a layer of fine sand produces water which is free from suspended solids.

The ammonia removal efficiency and elimination rate for the aerated activated carbon layer is shown in Fig. 5.

Complete removal of ammonia can be achieved at loading rates up to 0.5 kg amm.N/m^3.d, although the maximum removal rate is higher.

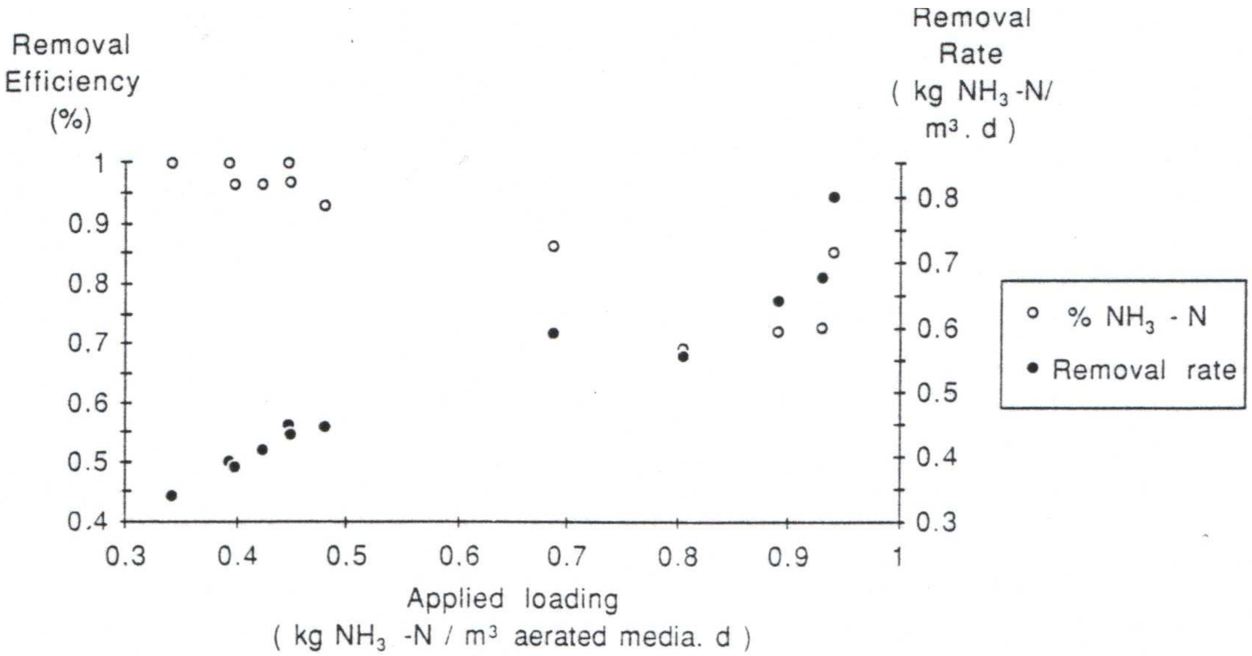

Fig. 5. Ammonia elimination rate and removal efficiency in a downflow aerated GAC/Sand filter
(Biocarbone: aerated height = 85 cm)

The polishing effect of the Biocarbone filter is shown in Fig. 6. For a water leaving the anoxie filter with low nitrate values, final residuals of both nitrite and ammonia are below the drinking water standards at a filtration rate of 5 m/h. If nitrite breaks through the denitrification reactor, the aerated filter is able to oxidize concentrations exceeding 10 mg/1 NO$_2$ back to NO$_3$ - even at higher filtration rates. Concentrations of residual ammonia are only above the limit of 0.5 mg/1 if the influent concentration is higher than 4 mg/'l and empty bed contact periods are reduced to below 10 mins.

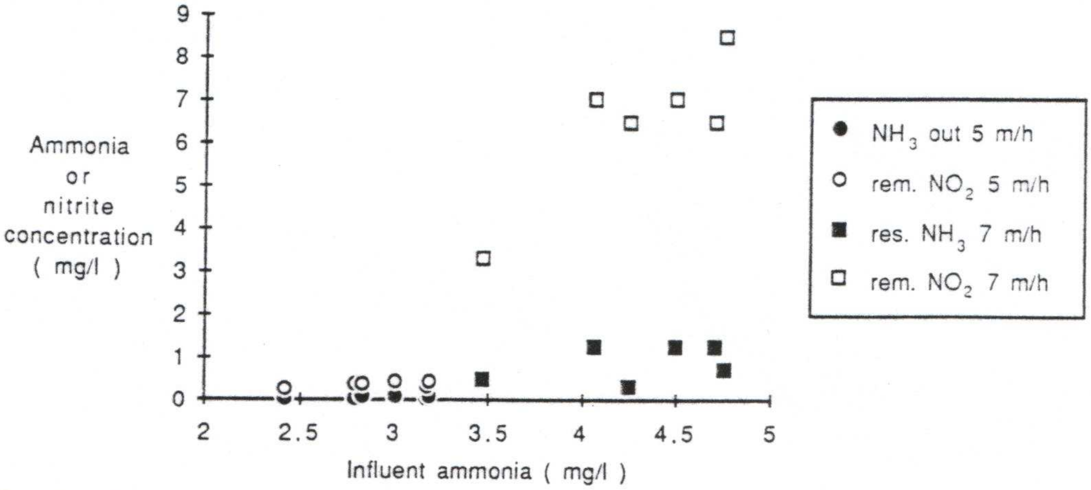

Fig. 6. Residual ammonia and removed nitrite concentration (mg/l) with different filtration velocities

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FULL-SCALE EXPERIENCES

ERAGNY.

In parallel with the pilot-scale studies, the first demonstration plant for biological nitrate removal was already in operation[38]. This plant, built at Eragny-sur-Oise in the outer Paris suburbs, was commissioned in June 1983. When the decision for the construction of a large-scale unit was taken, the operational experience at Eragny had confirmed the economical and technical feasibility of the process. In addition to the pilot results, the full-scale operational experience led to the optimization of chemical-dosing and backwashing techniques[39].

The 80 m^3/h plant is designed to treat 1.2 kg NO_3-N/m^3.d, and the average sludge production is 0.13 kg dry solids/kg NO_3-N/nr.d. Backwashing of the anoxie reactors, which is carried out every four days by timer control, can also be initiated by pressure sensors that react if the headloss reaches 0.5 bar. Water consumption for backwashing is about 1.5% of the treated flow.

To extend the DO limitations, biological aerated filtration in the Biocarbone process was used to reoxygenate the water, oxidize carbon and amm.N, and retain suspended solids in one single step. At Eragny, two double-layer aerated filters are designed to oxidize 0.15 kg NH3/m^3.d at 12°C. Aluminium sulphate is used as a coagulant at a dose rate of 5 g/m^3. Backwashing of the polishing filter is carried out automatically once every 48 h, resulting in a water loss below 3%.

Dennemont

Following pilot studies and the technical optimiz-ation of the process at Eragny, in 1986 a new plant was built at Dennemont serving about 50000 people. The capacity of this plant is 400 m3/h.

A flow diagram is shown in Fig. 7 and the operational data are summarized in Table I.

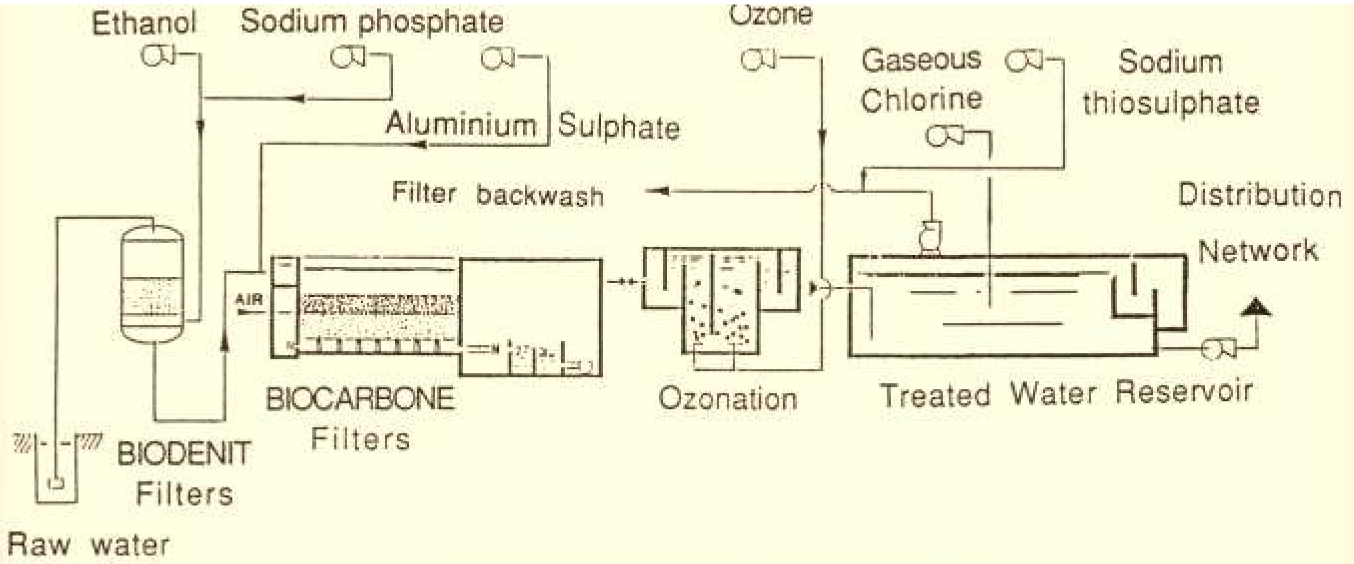

Fig. 7. Flow diagram of Dennemont plant

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TABLE 1. DENNEMONT TREATMENT PLANT: OPERATIONAL DATA

Parameter	Value	
Flow (m^3/h)	400	
Dosage of ethanol (mg/l)	34	
Dosage of phosphate (mg/l)	0.48	
	Denitrification (Biodcnit)	Postfiltration (Biocarbone)
Number	4	4
Surface (m^2)	8	20
Height of filter bed (m)	2	2.4
Feed flow rate (m^3/h)	400	400
Flow rate ($m^3/m^2.h$)	10	5
Empty bed contact period (min)	12	30
Bacteria support (mm)	3-6 (Biodagene)	1.7-3.4 and 0.8-1.2 (Coal and sand)

The water source is alluvial groundwater, and characteristics of the raw and treated water are shown in Table II. The sludge production is 32 kg/d, and ail the sludge is discharged to sewer.

TABLE II. WATER QUALITY AT GUERNES/DENNEMOST PLANT

Parameter	Raw water	Treated water
Temperature (°C)	12 -13	-
pH	*1.2*- 7.4	7.5 -7.6
Nitrate (mg/l)	40 -65	15
Nitrite (mg/l)	0.1	0
Ammonia (mg/l)	2.0- 3.5	0.01-0.02
Turbidity (NTU)	0.3	0.2
Phosphate (mg/l)	—	0.1
Orthophosphate (mg/l)	0.1	_
TOC (mg/l)	1.3	1
BDOC (mg/l)	<0.1	<0.5
Total aluminium (ng/1)	—	<20
Total alkalinity (mg/l)	30.0	29.5

TOC — total organic carbon
BDOC — biodegradable dissolved organic carbon

The calco-carbonic equilibrium is not markedly influenced, since bicarbonate is produced through denitrification and consumed by nitrifiers.
Phosphorus and aluminium levels are not significantly changed.

Ethanol was never detected at the outlet of the treatment plant, since a considerable safety margin for the removal of excess carbon is provided by the aerated filters.
Micropollutants were reduced by the biological System as shown in Table III.

TABLE III. MLCROPOLLUTANT REMOVAL AT GUERNES/DENNEMONT

Parameter	Raw water	Treated water
Total Kjeldahl nitrogen (ppm)	1.3	0.3
Cyanide (ng/1)	20.0	10.0
Carbon tetrachloride (^g/1)	2.0	3.8
Trichloroethylene (ng/1)	10.0	1.8
Tetrachloroethylene ((ig/1)	2 2	nd
111 Trichloroethane (ng/1)	28.0	5.0

nd = not detected

Three mechanisms can explain the removal of organic pollutants: (i) anoxie biological uptake[41]. (ii) stripping in the aerated filters[42], and (iii) activated-carbon adsorption[43]. The latter may be enhanced by bioregeneration of the aerated filters, and detailed studies are being carried out to quantify the effect of each removal option[44].

The treatment was started by seeding the anoxie reactors with backwash sludge from other plants to speed up the biological reaction. For the first few days water was recirculated onto the filters, and after ten days the denitrification reaction was complete. The flowrate was then increased up to the nominal value, which was reached after three weeks. The treated water was pumped to the sewer until an official analysis confirmed that the water was within the EC Drinking Water guideline. A slight overdosing of ethanol is advisable to guarantee sufficient denitrification performance and suppress the occurrence of nitrites (Fig. 2).

After a few months' operation, problems arose when nitrites were detected at the outlet of the anoxie reactors. A thorough examination of plant operations showed insufficient backwashing in the biological filters, which resulted in an accumulation of biomass in the media. The presence of old sludge, as well as the creation of preferential paths due to clogging, caused a partial stoppage of the denitrification process. A change in the washing sequences and an increase in the flow rate during rinsing completely overcame this problem. Further protection is provided by the ozonation stage downstream, which ensures a thorough oxidation of dissolved matter[45], and chlorination is practised before release of the water into the distribution network.

The performance of the biological reactors after a 24-h stoppage was monitored to check the reliability of the nitrogen removal following an incident.

Fig. 8 shows the concentrations of nitrate and ammonia at the outlet of the anoxie reactor, with samples taken every 15 mins.

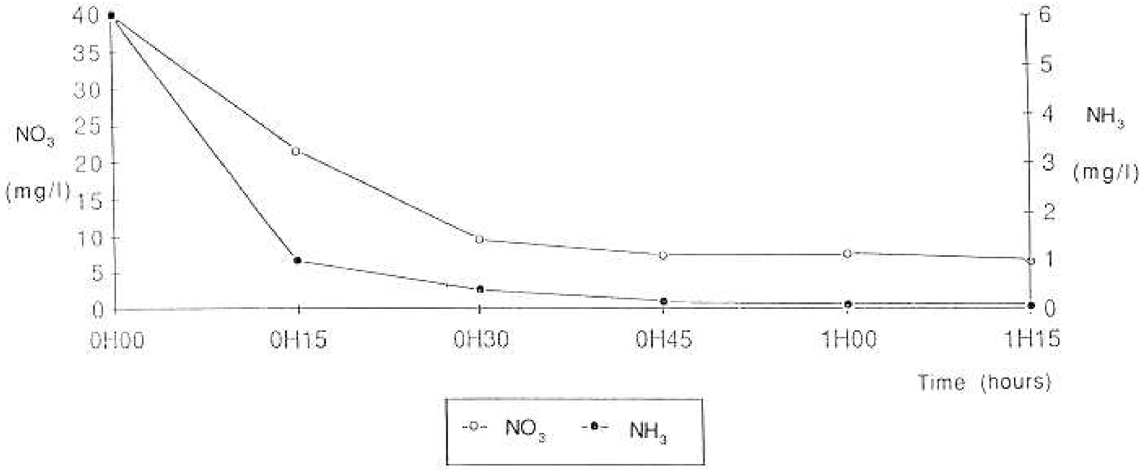


Fig. 8. Concentrations of nitrate and ammonia in anoxic reactor effluent after a 24-h shutdown

Nitrate removal is almost complete after 45 mins' operation. While some biomass becomes detached and hydrolyses during the absence of water feed, giving high residual ammonia levels, this is rapidly flushed out.

The residual amm.N concentration, even after the anoxie filter, is close to zero, since about 1 mg/1 is taken up by the heterotrophic biomass. The reaction of the polishing aerobic filters to the stoppage is shown in Fig. 9.

The peak of 6 mg/1 amm.N from the anoxie effluent is absorbed by the Biocarbone units, with only a minor breakthrough after 30 mins.

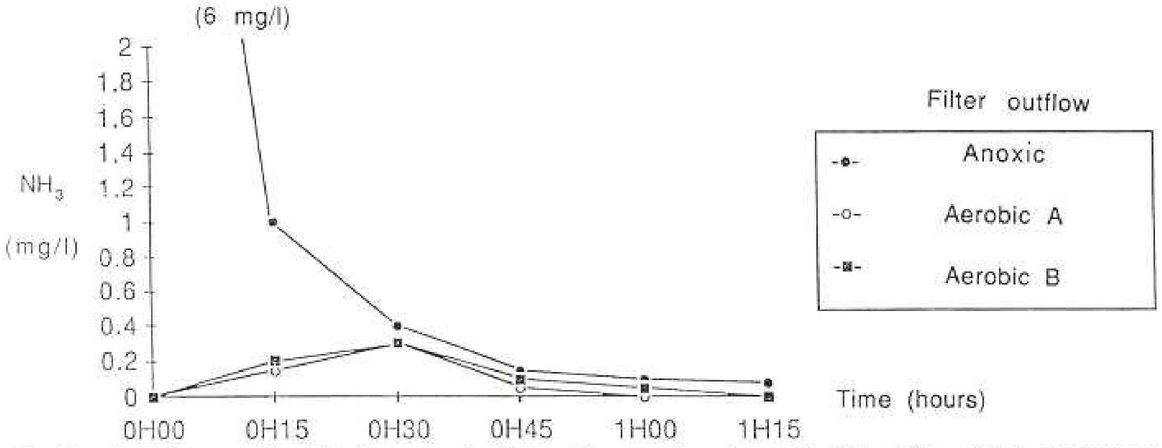
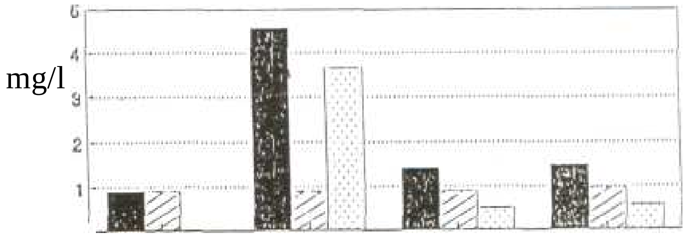


Fig. 9. Incoming and residual concentrations of ammonia of aerobic filter after a 24-h shutdown

Particular attention has been paid to the carbon balance of the plant[46]. Easily biodegradable substances released into the network may cause regrowth of bacteria[47], and since groundwater is almost free from easily biodegradable dissolved organic carbon, and ethanol is added, the efficient removal of this preferred substrate has to be ensured. Specifie methods have been developed to follow the type of carbon and its evolution through potable water treatment plants[48,49]. As shown in Fig. 9, traces of ethanol increase the biodegradability of residual total organic carbon after the anoxie filter, but the final quality after the Biocarbone filter is comparable to the raw water[46].



Water type > Untrealed Denitrified Aerobic filter Finished

Total (TDOC), refractory (RDOC) and biodegradable (BDOC) fractions of organic carbon

ECONOMIC ASPECTS

Funding the process of denitrification can create a problem for utilities that are not prepared for the inevitable added cost resulting from the treatment. The technical and economie feasibilities of both the heterotrophic biological method and the ion-exchange technique were confirmed on full scale, and about ten plants are operating in France. At present, these two methods are by far the most economical with regard to investment. If an ion-exchange based installation costs x, a heterotrophic biological installation costs about 2x, ail other circumstances being equal. On the other hand, a reverse-osmosis plant will cost approximately 8x and an autotrophic biological System can reach a cost of 12x following pilot-scale experiments on natural sulphur media . No experiments using nitrate reduction with hydrogen were carried out, but German data show slightly higher operating costs[18]. The total operating cost, expressed per cubic metre of treated water, is approximately the same for the ion-exchange system and the heterotrophic biological plant. The capital cost of the installation at Guernes was about 25 MFF (at 1985 prices). The 1986 revenue costs were studied in detail and resulted in a total operating cost (excluding waste treatment) of 0.8 FF/m3. This was split as follows: reagents 0.3 FF/m3; electricity 0.1 FF/m3;

The operating cost of a biological denitrification unit is comparable to an ion-exchange facility or to a convention al surface water clarification facility. However, denitrification treatment becomes necessary for waters for which the previous cost included only pumping and disinfection. A comprehensive study of denitrification, including the different technologies of control and their impact on water quality and consequences on the network (in addition to treatment cost), has recently been completed in the UK50.personnel (2h of supervision/d) 0.2 FF/m3; and maintenance and renewal of equipment 0.2 FF/m3.

CONCLUSIONS

1 -Biological filters for both ammonia oxidation and nitrate reduction simulate processes occurring in the environment. To remove nitrogen found in groundwater, these natural reactions were enhanced in industrial installations consisting of an anoxie fixed-bed reactor in series with an aerobic filter. Extensive pilot tests established the limits of the two biological treatment units: a 15-min retention period was necessary to denitrify 70 mg/l of nitrate, and for downstream polishing a two-layer aerated filter operating at 5 m/h was adopted.

2- The design data were applied in full-scale treat ment plants. The first plant at Eragny (80 m3/h), which was commissioned in 1982, confirmed the feasibility of the process and optimized the operation of the treatment system. In 1985 a larger installation (400 m3/h) was built at Guernes-Dennemont, where ammonia and nitrate were found simultaneously in the ground water. By applying innovative biotechnology on a large scale, the complete removal of nitrogen and organic compounds was achieved.

3- More than 10 plants for nitrate removal are operating in France today, working with both ion exchange and biological removal.The application of one or the other process is dependent on local conditions.

4- The operating costs of the nitrate removal systems are 0.7-0.9 FF/m3.

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DISCUSSION (Abridged)

Dr A. L. Downing (Binnie & Partners), opening the discussion, said that being wise after the event one might have been prepared to accept that the individual stages of the overall process would work - given the correct design and operating conditions. After all, the first stage was similar to the process used since the early 1970s for denitrifying wastewaters and was one with which he was familiar; for example in Canberra, Australia. A difference was that in Canberra methanol was used as the carbon source (rather than ethanol), and the filter medium was slightly different. With regard to the second stage, in the Severn Trent region a method of oxidizing organic matter and ammonia had been used since the early 1970s at the Strensham and Tewkesbury works, where slightly-polluted river water was passed by upflow through a sludge-blanket clarifier, and the nitrifying organisms and some hetero-trophs grew on the nuclei in the 'blanket'. The difference was that there was no activated carbon, and because there was no introduction of air the ability of the process was limited to oxidizing about 2 mg/l of amm.N. Additionally, the power of the activated carbon to remove organics was well known, and it had been used for many years in water and wastewater treatment for this purpose.

He said that the authors had had sufficient imagination to ensure that all these processes could be linked together in a novel configuration and to define the design and operating conditions needed to make it all work.

Dr Downing asked whether ethanol had been chosen in preference to methanol purely on safety grounds. He thought that in France, as in the UK, methanol might be cheaper than ethanol.

He enquired how the ethanol dose was proportioned to nitrate, and if any sensing device was used to adjust the dose under fluctuating conditions. He said that he was not clear whether it was the general practice to slightly overdose the ethanol to maximize the reaction rates.

Dr Downing asked if the plant was sized to cope with the load at the lowest temperature and the highest anticipated concentrations of nitrate and ammonia. He wondered what was known of the dynamic response of the plant; would it immediately cope with the fluctuations in load, or was there some temporary deterioration in performance whilst it adjusted?

He said that there was a significant quantity of sludge produced from a high nitrate source, which the authors had referred to, being released to sewer. He asked if, in France, a charge was levied for such release to a sewage-treatment works, and if a carbon regeneration requirement was included in the quoted costs.

Mr G. F. G. Clough (Howard Humphreys and Partners) asked whether the cost for the ion-exchange method included the cost of disposing of the spent regenerant.

Professor D. G. Stevenson (PWT Projects Ltd) enquired about intermittent operation of the plant. He said that one advantage of an ion-exchange process was that it could be stopped and started instantly. He considered that a biological process normally had a significant start-up time. He asked, for example in the event of a power interruption, what outage time could be tolerated before problems were experienced.

Authors' Reply

In reply to Dr Downing, **Mr Rogalla** confirmed that ethanol was used because of the concern for public health This had been requested by the public health authorities who also allowed the use of other organic substances such as acetic acid and glucose. It had been considered that ethanol was the most simple structure, and therefore the one that gave the least sludge generation.

With regard to dosing the ethanol, he explained that plants operating on well water would normally run at a constant flow rate and consistent nitrate concentration; therefore it was unnecessary for the ethanol dose to be adjusted. However, it could be undertaken by linking flow and concentration measurements to a dosing device.

Mr Rogalla said that there was a tendency to overdose ethanol because it had been found that the reaction was much more stable and there was less danger of nitrite breakthrough. If the dosing was correct, the reaction of denitrification was complete before the end of the reactor, and neither ethanol nor nitrite was detected in the outflow of the anoxic reactor.

He said that the activated carbon was not so much used for its adsorption capacity but rather for its fixation of bacteria, and therefore did not rely on regeneration in the physicochemical manner. The carbon was not changed, but the system relied on biological regeneration. Whenever the bacteria had no substrate, they would take whatever was fixed in the carbon. In addition to the high-rate filter, this principle had been applied in large river-water treatment plants where there was a biological activated-carbon stage in which biological growth was encouraged (for instance through ozone or other means of high aeration), and therefore all the biodegradable matter was absorbed or degraded. This aspect also gave a partial answer to the question of feed fluctuation in that there would be some substrate stored in the carbon, and therefore the bacteria would not be so sensitive to the absence of substrate. However, it was a biological process. and fluctuations would have an influence. The biomass concentration which could be retained in a fixed-film system was high; the bacteria were often not at the limit of their capacity and if there was a fluctuation they were able to absorb it.

With reference to temperature fluctuations, Mr Rogalla said that work had recently been carried out using biological reactions at low temperatures. Most underground water sources in France were in excess of 10°C, so there were no problems. In laboratory work at 5-6°C it had been found that the decrease of activity had been much lower than expected.

He said that for a nitrifying filter it took about three weeks to achieve stability, but once the nitrifiers were fixed on the grain they remained - even during a shutdown of a couple of days. He felt that one week was a critical period, but if the filters were left aerated this overcame any problem.

Replying to Mr Clough. he said that the cost calculations did not include handling the sludge or the brine solution. Normally a cheap solution for sludge was by discharging to sewer or discharging to an environmentally-acceptable receiving water. No charge was made for discharging the sludge or the resin regenerant to sewer. In fact discharge of the nitrate brine to sewer would have a beneficial effect on the receiving sewage-treatment works by providing oxygen supply in the form of the nitrate.

He said that a similar system had been applied more extensively to wastewater treatment because it was felt that it could considerably reduce the area needed for treatment since it was unnecessary to install a separate biological reactor and clarifier. One did not worry about sludge age since the nitrifiers were retained in the system.

Also there was no concern over sludge recycling, sludge settling or bulking sludge.

He said that in France there were about 15 large-scale filters of this kind, the largest one treating a population equivalent of about 150000.