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EUROPEAN OPERATING EXPERIENCE WITH A HIGH RATE PROCESS FOR NITROGEN CONTROL

A.Warakomski
Mixing and Mass Transfer Technologies
Lotepro Environmental Systems & Services
8 John Walsh Blvd., Suite 423
Peekskill, NY 10566
R. van Kempen
J. W. Mulder
M. C. M. van Loosdrecht

ABSTRACT

Abstract SHARON ® is a very cost-effective treatment system for the total removal of nitrogen components, thru nitrification/denitrification, from wastewater flow streams containing high concentrations of nitrogen. The system is used in the treatment of municipal wastewater side streams from both dewatered digested primary sludge and waste activated biosolids to achieve high total overall nitrogen removal. It is also used for the treatment concentrate from sludge and biosolids drying facilities, of high strength land fill leachate, and manure treatment wastewaters.

SHARON ® is a high rate process for the removal of total nitrogen operating with minimal sludge retention time. Due to differences in growth rates of the bacterial species at the process design temperature (30-40 ^{O}C) a selection can be made wherein the nitrite oxidizing bacteria can be washed out of the system while ammonia oxidizing bacteria are retained along with denitrifying bacteria. Using this metabolic mode of operation allows for a 25% reduction in aeration energy required for nitrification and a 40% reduction in the amount of BOD addition needed for denitrification. In addition since the process is accomplished in a side stream there are savings in mainstream reactor costs.

The pertinent principles of both nitrification and denitrification and also the SHARON ® process design parameters are developed. Three full-scale SHARON ® systems have been constructed at large wastewater treatment plants in Europe and a fourth is under design. The results of the full scale operation at the Rotterdam, Dokaven Plant, Netherlands, are presented. The Utrecht Plant is illustrated.

KEYWORDS

denitrification, nitrification, total nitrogen removal, side stream treatment, SHARON ®

SHARON® an acronym for **S**ingle reactor system for **H**igh activity **A**mmonium **R**emoval **O**ver **N**itrite

INTRODUCTION

This paper introduces SHARON®, a new process for total nitrogen removal which allows for nitrification/denitrification at minimal SRT values, resulting in a substantially smaller reactor volume than is currently required for conventional nitrification and denitrification. In addition the process allows for both a savings of twenty five percent (25%) in oxygen transfer energy and forty percent (40%) in carbon feed for denitrifying bacterial growth as compared to conventional processes. The core concepts on which the process is based is that at temperatures above 15^{O} C, and especially between 30-40^{O} C, the growth rate of the nitrifying bacteria are greater than the nitrafying bacteria and also that denitrifying bacteria are capable of anoxic conversions of nitrite to nitrogen gas.

MICROBIOLOGY and BIOCHEMISTRY

There are several different bacteria that convert ammonium to nitrate [(1)]:

	Genera
Ammonia Oxidizers (nitrifying bacteria)	Nitrosomonas, Nitrosococcus, Nitrosopira, Nitrosolobus, and Nitrosovibrio
Nitrite Oxidizers (nitrafying bacteria)	Nitrobacter, Nitrospina, Nitrococcus, and Nitrospira

In addition the biochemistry of these chemolithoautrotrophic bacteria can be expressed several ways stoichiometrically one of which is [(2)]:

Nitrifying Bacteria:

$$1)\ NH_3 + 1/2O_2 \longrightarrow NH_2OH$$

$$2)\ NH_2OH + O_2 \longrightarrow NO_2^- H_2O + H^+$$

Nitrafying Bacteria:

$$3)\ NO_2^- + 1/2O_2 \longrightarrow NO_3^-$$

The initial step involves mono-oxygenase which uses NADH as an electron donor and the first product of nitrification is hydroxylamine (NH_2OH). There is no energy generated in this step, indeed energy is used up via the oxidation of NADH. The hydroxylamine is then oxidized to nitrite, and via electron transport phosphorylation through a cytochrome system ATP formation occurs. The nitrafication is carried out by a nitrite oxidase system, ATP is generated by an electron transport phosphorylation and the electrons are transported to O_2 via cytochromes. We lump both bacteria together in practice as "nitrifiers" and call the whole step wise process "nitrification".

A wide range of bacteria has been found to carry out denitrification; these bacteria are both heterotrophic and autotrophic [(3)].

Genera:
Achromobacter, Acinetobacter, Agrobacterium, Alcaligenes, Arthobacter, Bacillus, Chromobacterium, Corynebacterium, Flavobacterium, Hypomicrobium, Moraxella, Neisseria, Paracoccus, Prionibacterium, Pseudomonas, Rhizobium, Rhodopseudomonas, Sprillum, and Vibrio.

These bacteria function on multiple metabolic pathways, of course not all similarly. They can reduce oxygen, nitrate, nitrite, nitrious oxide, and nitric oxide and use those compounds as electron acceptors, again not all similarly. These bacteria can use a wide range of organic substrates as a carbon source, although each genus has its specific requirements. Under autotrophic denitrification, some of these bacteria can use carbon dioxide or bicarbonate as the carbon source instead of organic carbon for growth.

The accepted stoichiometry for various carbon feed sources is:

Methanol [4]

$$5CH_3OH + 6NO_3^- \longrightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$$

Acetic Acid [5]

$$5CH_3COOH + 8NO_3^- \longrightarrow 4N_2 + 5CO_2 + 6H_2O + 8OH^-$$

Sewage [6]

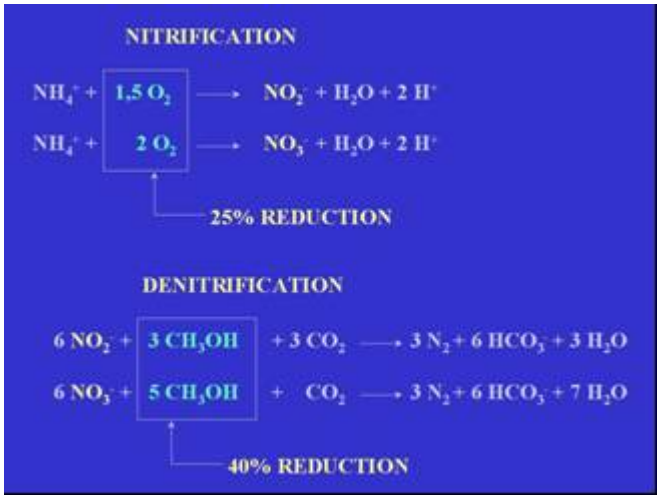
$$C_{10}H_{19}O_3N + 10NO_3^- \longrightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^-$$

There are two types of nitrate nitrite reductions-assimilative and dissimilative. Assimilative reductions "fix" nitrogen as ammonia. In dissimilative reduction nitrate then nitrite is used as the electron acceptor in energy generation. Under most conditions with most bacterial species the end product is nitrogen gas. Oxygen represses the synthesis of the nitrate and nitrite reductases, which are membrane bound, thus the reactions occur only under anoxic conditions. The reduction of nitrite is carried out by nitrite reductase and proceeds to nitrogen gas via the intermediates nitric oxide and nitrous oxide. The facultative bacteria such as Pseudomonas and Bacillus implement this metabolic pathway. Thus we have a step wise reduction:

NO_2^- NO N_2O N_2

The growth rates of nitrifying bacteria such as Nitrosomonas are significantly different from nitrafying bacteria such as Nitrobactor. At low temperatures up to 12^OC the growth rate of Nitrobactor is higher than that of Nitrosomonas. Above 12^OC Nitrosomonas growth rate is higher than nitrobactor, becoming significantly higher above 25^OC.
On a conceptual basis a reactor can be designed to take advantage of these principles to provide total nitrogen removal from a wastewater. The biochemistry results in significant reductions in the required oxygen to be transferred for oxidation and also in the amount of carbon addition required for bacterial growth in denitrification[7] **(See Figure 1. "SHARON ® BIOCHEMISTRY")**

FIGURE 1
SHARON ® BIOCHEMISTRY

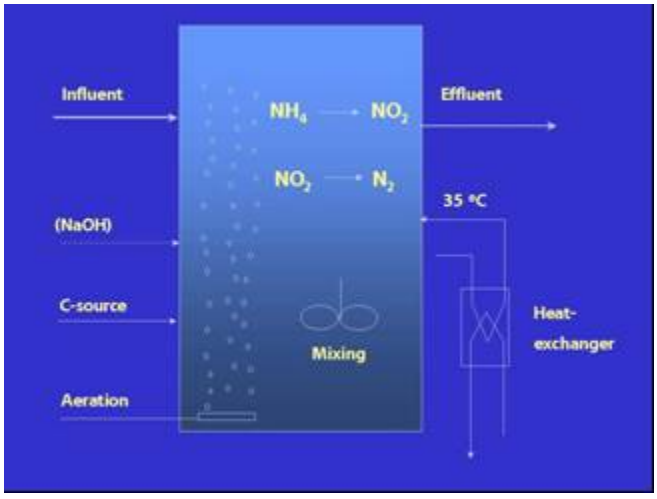


Since the oxidation of ammonia is taken only to nitrite and nitrite is reduced instead of being taken to nitrate and having the nitrate reduced there is a 25 % reduction in the oxygen requirements and a 40 % reduction in the carbon requirements.

SHARON ® REACTOR DESCRIPTION[8])

The SHARON ® reactor which accomplishes this is run at a minimal sludge retention time and elevated temperature in order to select the Nitrosomas bacteria over the Nitrobactor bacteria. It is run first in an oxic then anoxic mode either in time or space to accomplish both oxidation and reduction which results in nitrification and denitrification, without nitrafication The reactor can be run as a intermittent aerated reactor or a continuous flow staged reactor **(See Figure 2. "SHARON ® REACTOR SCHEMATIC").**

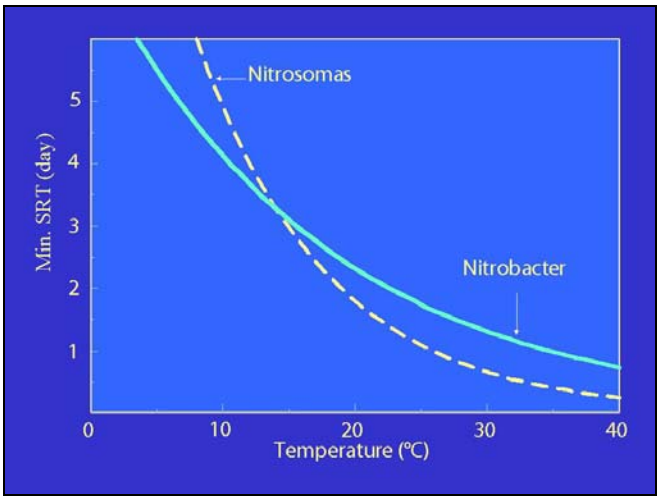
FIGURE 2
SHARON ® REACTOR SCHEMATIC



A characteristic feature of the reactor is that the biochemistry takes place without sludge retention that is the sludge retention time is equal to the liquid's hydraulic detention time;

again this is to allow selection of the Nitrosomas bacteria **(See Figure 3. MINIMUM SLUDGE RENTION TIME AS A FUNCTION OF TEMPERATURE).** There is no need or attempt made to develop large clusters of microbial floc, indeed the reactor is run with free cell mass or small clusters of bacteria.

FIGURE 3
SRT_{min} as a function of TEMPERATURE

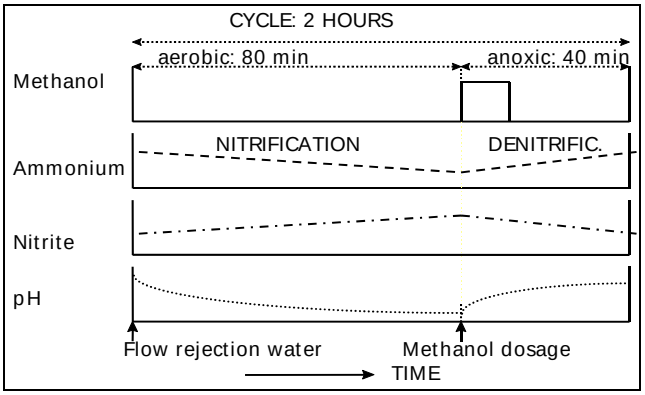


It is obvious from FIGURE 3 that the reactor will operate best in the range from 25-40^{O}C. The biological conversion of ammonia by this means with the influent at ammonia concentrations of about 1000 mgN/liter will cause a temperature rise of more than 10^{O}C per gram of nitrogen removed per liter. Therefore heat production has to be considered in the process design.
Since the growth rate of Nitrosomonas is pH dependent, pH is another important process parameter. The bicarbonate in both the influent, from the preceding anaerobic processes, and also from the denitrification process compensates for the acidifying effect of the nitrification process; both will provide 50 % of the alkalinity requirement. However CO_2 stripping from the reactor needs to be accomplished in order to allow full use of the bicarbonate.

By using intermittent aeration one can accomplish both nitrification and denitrification in a single reactor. The length of the aeration period is a function of inlet flow and pH. During aerobic periods the pH will decrease and during anoxic periods the pH will increase because of the biochemistry of the processes. **(See FIGURE 4. REACTOR CONDITIONS CORRELATED WITH OXIC and ANOXIC PERIODS).**

FIGURE 4

REACTOR CONDITIONS CORRELATED WITH OXIC and ANOXIC PERIODS



PROCESS DEVELOPMENT [9]

A problem is often the mother of invention. At the Rotterdam, Dorkhaven, Netherlands, Wastewater Treatment Plant there was little area available for implementing the new stringent total nitrogen removal requirements. Many processes were investigated. The site restrictions created a situation where "outside the box" thinking prevailed. At the Delft University of Technology Hellinga, Heijnen, and Loosdrecht synthesized the concept and tested it on the laboratory scale [10]. Then a scale up mathematical model was developed to design the full scale facility. An economic analysis of several different technologies for N-removal showed that the new process (SHARON ®) was the most cost effective of all the processes **(See TABLE 1. COMPARISON OF TECHNOLOGY FOR SIDE STREAM TREATMENT PLANT).**

TABLE 1
COMPARISON OF TECHNOLOGY FOR SIDE STREAM TREATMENT PLANT

	Production chemical sludge	Production biological sludge	Energy requirements	Operation	Cost estimate* Euro/kg N
Air stripping	yes	no	average	average	6.0
Steam stripping	yes	no	high	complex	8.0
MAP/CAFR process	yes	no	low	complex	6.0
Membrane bioreactor	no	yes	high	average	2.8
Biofilm airlift reactor	no	low	average	average	5.7
SHARON® process	no	low	average	simple	1.5

* Cost estimate based STOWA (1996) for WWTP capacity of 500,000 pe [11].

At the Rotterdam Dokhaven plant there was no area available for extension, therefore a post thickener was taken out of operation and converted to a SHARON ® reactor. The

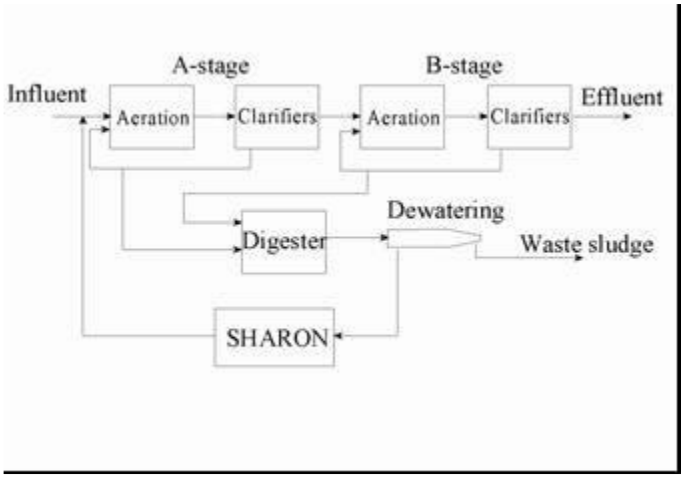
volume of the post thickener is 1800 m^3 exceeding the process design requirements (1,150 m^3). The extended volume of 1800 m^3 provides the flexibility to modify process conditions, for example during the start up phase and ensures spare capacity when needed. Grontmij Water and Wastewater Management in cooperation with the Water Authority ZHEW did the detailed design of the SHARON ® reactor and ancillaries **(See TABLE 2. "DESIGN PARAMETERS ROTTERDAM, DOKHAVEN PLANT, THE NETHERLANDS).**

TABLE 2
DESIGN PARAMETERS
ROTTERDAM, DOKHAVEN PLANT THE NETHERLANDS,

Design Parameter	Dimension	Value
Tank Volume	m^3	1800
Flow, design	m^3/hour	31.5
Flow, maximum	m^3/hour	50
N-load, design	kg/day	540
N-load, maximum	kg/day	830
NH_4, influent	mg/l	1000-1500
Retention Time $_{aerobic}$	days	1
Retention Time $_{anoxic}$	days	0.5-1.5

The reactor was designed for treatment of the sidestream of recycled wastewaters from biosolids treatment and processing. **(See Figure 5. "FLOW SCHEMATIC")**

FIGURE 5
FLOW SCHEMATIC



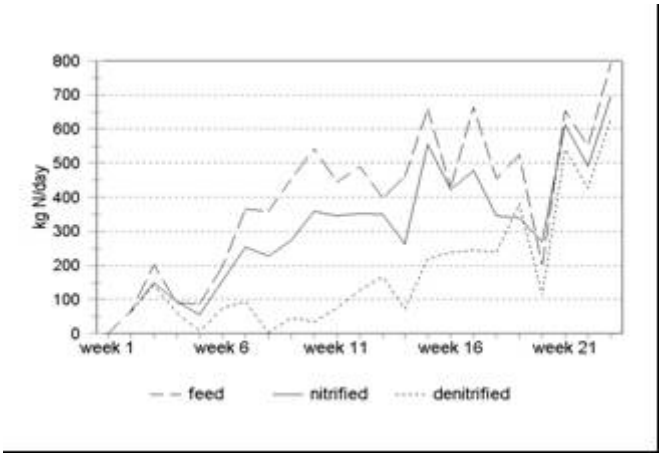
STARTUP AND OPERATION

The reactor **(See Figure 6. "SHARON ® REACTOR ROTTERDAM, DOKHAVEN PLANT, THE NETHERLANDS, ")** was initially filled with river water and heated to $30^{O}C$.

FIGURE 6
SHARON® REACTOR
ROTTERDAM, DOKHAVEN PLANT, THE NETHERLANDS

Then it was seeded with waste activated sludge. The flow was gradually increased in stepwise increments. At seven weeks the reactor was at full flow and load. **(See Figure 7. "INCREASE IN LOAD OVER TIME")**

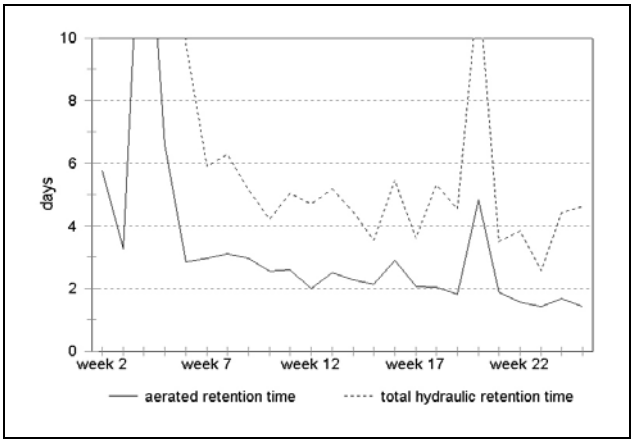
FIGURE 7
INCREASE IN LOAD OVER TIME



The average nitrogen load in the recycle stream was 520 kg N/ day. The feed to the reactor was not constant, but depended upon the amount of the plant's processed biosolids. The flow variation was between 0 and 980 m^3/day. The recycle stream's ammonia concentration was on average 1230 mg N/ l with a maximum of 1530 mg N/ l, higher than the design value of 1000 mg N/l

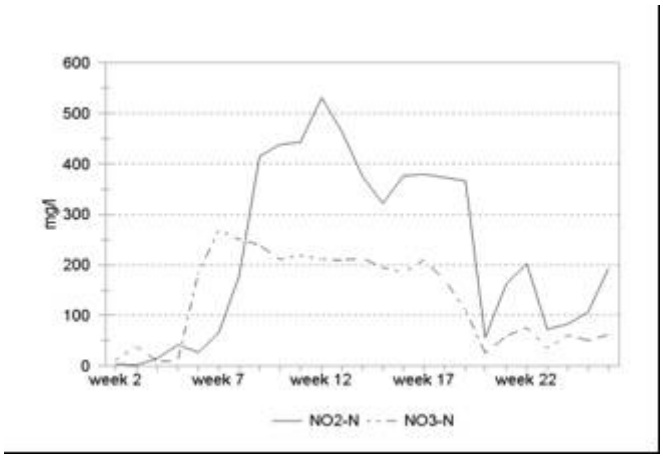
Both the reactor's hydraulic and oxic detention times were gradually decreased. At the 18th week the retention times reached design. **(See Figure 8. "HYDRAULIC AND OXIC RETENTION TIMES")**

FIGURE 8
HYDRAULIC AND OXIC RETENTION TIMES



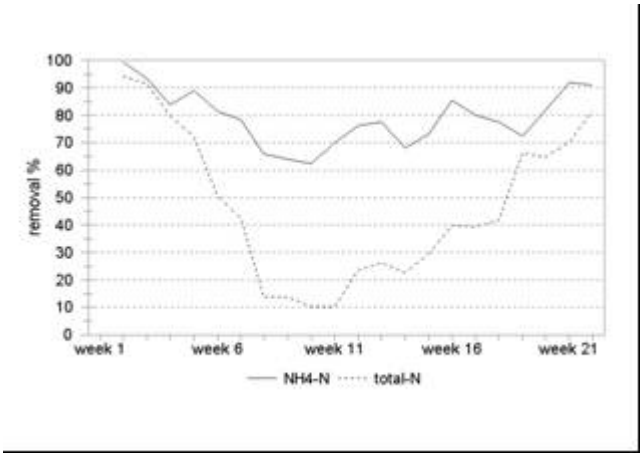
Ammonia was initially converted to both nitrate and nitrite. This is attributed to the long oxic retention time and bacteria present in the seed. Both nitrate and nitrite were then partially reduced. At week 19 the process stabilized. The process proved to be stable and insensitive to variations of the load or other disturbances, such as high influent SS concentrations **(See Figure 9. "WEEKLY AVERAGED NO_X CONCENTRATIONS")**

FIGURE 9
WEEKLY AVERAGED NO_X CONCENTRATIONS



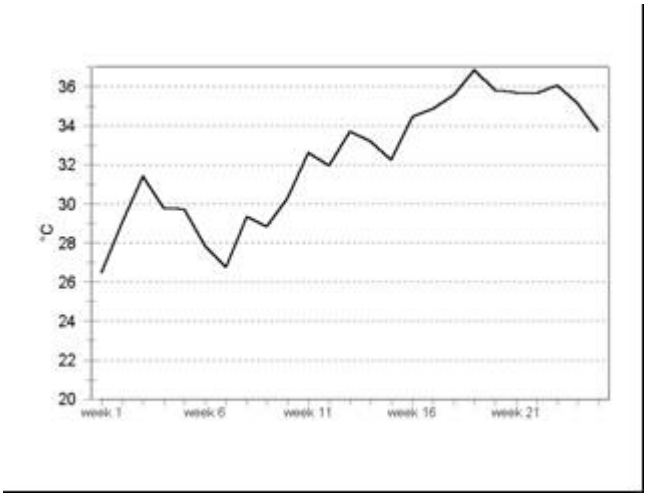
The initial removal of total nitrogen was above 90%. A malfunction of the instrumentation and control for pH caused this efficiency to decrease to 10%.The pH had dropped to 6.5. After repair and an increase in methanol dosing the pH increased to 7.0. The removal efficiency then steadily increased back to 90%. A similar trend was observed for ammonia nitrogen although the ammonia removal never dropped below 60%. **(See Figure 10. "WEEKLY AVERAGED REMOVAL EFFICIENCIES")**

FIGURE 10
WEEKLY AVERAGED REMOVAL EFFICIENCIES



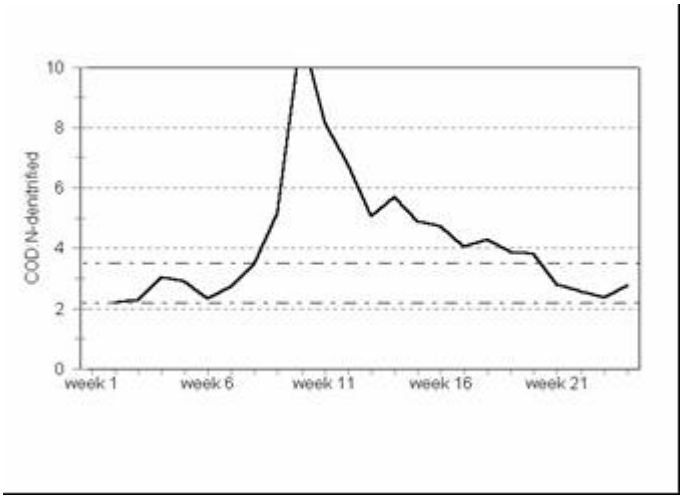
During the initial period the reactor temperature was lower than the design value of $35^{O}C$ due to the long hydraulic retention time and a winter startup. The post thickener used as the reactor was not insulated which caused significant heat loses. The temperature was gradually increased until no external heating was required. **(See Figure 11 "REACTOR TEMPERATURES")**

FIGURE 11
REACTOR TEMPERATURES



The denitrification mathematical model including biomass yield would predict a stoichiometric demand of 3.5 g_{COD}/ g N denitrified if nitrate were the metabolic pathway that was followed and 2.2 g_{COD}/ g N denitrified if nitrite was the metabolic pathway that was followed. During the period after the seventh week the ratio was high due to overdosing of methanol and suboptimal control. This situation was brought under control and the ratio decreased to 2.4 by the 18th week, which indicates denitrification via the nitrite metabolic pathway. **(See Figure 12. "METHANOL ADDITION")**

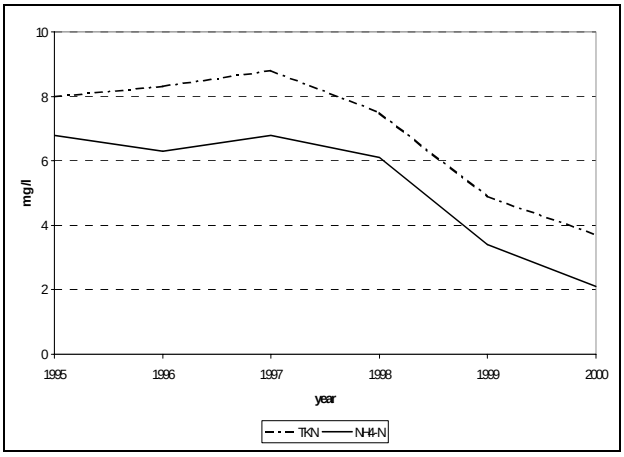
FIGURE 12
METHANOL ADDITION



The effect of the SHARON^{R} reactor's operation on the overall plant effluent was positive decreasing the total and ammonia removal. **(See Figure 13. "DOKHAVEN PLANT EFFLUENT RESULTS")**

FIGURE 13

ROTTERDAM DOKHAVEN PLANT EFFLUENT RESULTS



OTHER FACILITIES

A second plant is in operation at Utrecht (maximum N-load 900kg/day), The Netherlands, a third is under construction in Zwolle (maximum N-load 700 kg/day), The Netherlands and a fourth is in design for Beverwijk (maximum N-load 1200 kg/day), The Netherlands. **(See Figure 14. "SHARON® UTRECHT, THE NETHERLANDS)**

FIGURE 14
SHARON® UTRECHT, THE NETHERLANDS

CONCLUSIONS

A novel reactor (SHARON®) has been implemented on full scale basis and demonstrated a hitherto unutilized metabolic pathway for total nitrogen removal. The reactor converts ammonia mainly to nitrite by oxidation at a minimal sludge retention time at elevated temperatures. In this mode of operation the reactor selects Nitrosomonas over Nitrobactor by washout of Nitrobactor. The nitrite is then anoxically converted to nitrogen gas.

The ability to select Nitrosomonas over Nitrobactor has been proven.

The methanol, used as a carbon source, was dosed at the minimum ratio of 2.4 kg COD/ kg N removed indicating N- removal over nitrite.

The heat production in the reactor is significant due to the rapid conversion of high concentrations of ammonia.

The process proved to be insensitive to influent high TSS concentrations.

The control of the reactor's pH by the production of alkalinity from denitrification has been proven.

Ammonia removal efficiencies of greater than 90% have been proven.

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AUTHORS: R. van Kempen is with Grontmij Water and Waste Management, De Bilt The Netherlands; J.W. Mulder is with the Water Authority Hollandse Eilanden and Waarden, Dordrecht, The Netherlands; M.C.M. Loosdrecht is with the Department of Biochemical Engineering, Delft University of Technology, Delft, The Netherlands; A. Warakomski is with Mixing and Mass Transfer Technologies INC. Correspondence should be addressed to Mr. Warakomski at Suite 818, 8833 North Congress, Kansas City, MO 64153 (awarakomski@m2ttech.com) (FON 816-584-1969, FAX 816-584-1970)

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